ISSN: 2414-1895 DOI: 10.6919/ICJE.201909_5(10).0012

Study on variable magnetic adsorption performance of wheeled mobile wall climbing robot

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Abstract

A non-contact permanent magnet adsorption wall climbing robot is designed for different types of wall conditions. The robot consists of a permanent magnet adsorption device, a mechanical base and a drive circuit. The arrangement of the permanent magnet adsorption part was analyzed by Comsol software. The finite element simulation of the adsorption force generated by the permanent magnet adsorption unit was carried out under the wall thickness of different thicknesses and the working air gap of different distances. Finally, the accuracy of the design is verified by comparison of actual tests and simulation results.

Keywords

Climbing robot, permanent magnetic adsorption, finite element simulation, Comsol.

1. Introduction

Climbing robot is a kind of special robot which works in harsh, dangerous and extreme environments has developed quite rapidly in recent years. In the nuclear industry, petrochemical enterprises, construction industry, fire department, shipbuilding industry. The wall-climbing robot has a wide range of applications, so more and more people are paying attention to their research. The wall-climbing robot must obtain two basic functions： the adsorption and the ability of moving on the wall. Compared with some common climbing robots, such as vacuum adsorption robots and Negative pressure adsorption robots,the permanent magnet adsorption method has strong adaptability to the wall surface, and the adsorption force is much larger than the vacuum adsorption. Therefore, it has a higher safety factor and better load capacity and widely used in magnetically conductive material workplaces like ship surface rust removal, industrial boiler flaw detection, tubing crack detection. The wall-climbing robot generally works on the vertical wall surface, it is not only necessary to ensure that the robot can be stably adsorbed on the wall when it is static, but also to ensure that the wall can be safely adhered to during the walking of the robot. However, the greater the magnetic attraction force, the greater the resistance to motion when the car moves [1, 2, 3]. Therefore, this paper designs and manufactures a permanent magnet type wall-climbing robot with adjustable adsorption mode. The adsorption efficiency can be improved by adjusting the distance between the permanent magnet adsorption mechanism and the wall surface to improve the speed of robot movement. The layout of permanent magnet and the adsorption force of different wall thickness are analyzed by finite element method. It provides reference for the design of permanent magnet adsorption device.

2. Robot body design

This system mainly consists of mechanical bottom plate, control system and drive circuit. The permanent magnet adsorption mechanism is fixed on the bottom of the trolley through the screw rod and polished rod. When the robot is placed vertically on the adsorption surface, a pair of interaction

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forces will be generated between the permanent magnet adsorption mechanism and the adsorption surface, so that the robot can be stable adsorption on the adsorption surface. At the same time, the other end of the screw rod is connected with the stepper motor through a coupling, which drives the permanent magnet adsorption mechanism up and down to move, so as to control the distance between the permanent magnet adsorption mechanism and the adsorption surface.

3. Mechanical design

3.1 Bottom plate design

Due to the requirements of flexible robot movement, simple operation, so we use wheeled movement mode [4]. The common wheel structure of wall climbing trolley is three-wheel and four-wheel. In the process of attaching to the wall, only one point in the front section of the wall-climbing robot is connected with the adsorption surface, which makes it easy to roll over and drop the robot when the adsorption force is low. Considering that four-wheel design is adopted to ensure the subversion resistance and balance of the robot in the wall-climbing process, the two driven wheels in the front segment greatly improve the stability of the wall-climbing robot. Due to the use of aluminum alloy plate as the robot chassis material, the increase in chassis weight is almost negligible.

3.2 Adsorption and drive selection

At present, the popular adsorption methods of wall-climbing robot include magnetic adsorption, vacuum adsorption, thrust adsorption and biomemetic adsorption. This design adopts permanent magnet adsorption. The soleplate design of the magnetic adsorption mechanism is shown in Figure 1. The permanent magnet adsorption mechanism is fixed on the bottom plate of the robot by a polished rod, and connected with the stepping motor by a screw rod and a coupling in the middle. The stepping motor controls the permanent magnet adsorption mechanism to move up and down parallel to the bottom plate of the robot, so as to control the adsorption force between it and the adsorption surface, as shown in Figure 2.

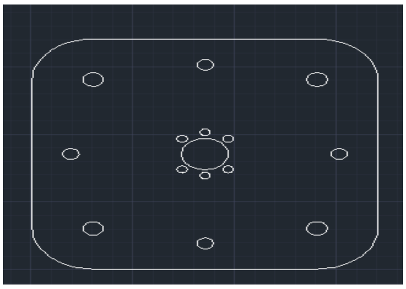
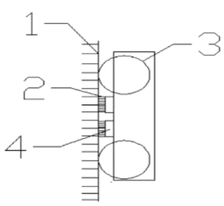


Figure 1. CAD diagram of adsorption bottom board

Figure 2. Adjustable magnetic part design

3.3 Operating principle

The adsorption device of the robot consists of a permanent magnet and a fixture. Figure 3 shows the working principle of the non-contact adsorption device. A certain working air gap is reserved between the wall and the adsorption device [5].



1-Magnetic wall 2-Magnetic line of force 3-Wheeled mobile device 4-Permanent magnets

Figure 3. Schematic diagram of adsorption device

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4. Adsorption simulation of permanent magnets

4.1 4Establishment of simulation model and material definition

The simulation of the permanent magnet adsorption unit is established by Comsol Multiphysics. We test the different adsorption forces by changing the gap between the adsorption device and the wall and the thickness of the working wall. Because the 3D model can more intuitively reflect the limitations of the problem description and the limitations of the two-bit model, the three-dimensional modeling method is adopted. This model uses the "magnetic field, no current" physics field in Comsol, and considering the actual medium and small robot speed is slow, it can be approximated as a static magnetic field. The external conditions are temperature T = 293.15 K and absolute pressure PA = 1 atm (100 kPa). The adsorption device includes a permanent magnet material and a magnetic yoke that guides the magnetic flux. The permanent magnets are made of high-performance rare earth permanent magnet material NdFeBN35. The performance parameters are shown in Table 1.

The relative magnetic permeability was set to 1.05 during the simulation. The magnetic yoke iron is made of 430 stainless steel, and the relative magnetic permeability is set to u_r=3000. The wall material is made of iron plate that comes with the software. Construct a sphere with a radius of 30cm to simulate the external environment and working gap of the robot. The material property is set to air, Br=1.0[6,7].

4.2 Theoretical basis of finite element analysis

The differential form of the static magnetic field Maxwell equation is,

$$\nabla \times H = J \qquad \nabla \bullet \mathrm{B} = 0 \tag{1}$$

Where H is the magnetic field strength; B is the magnetic induction intensity; J is the current density. In the field of no electric field, J=0.

Since the media involved in the adsorption device are all isotropic, they are satisfied,

$$\mathrm{B} = \mu H \tag{2}$$

Where is the permeability of the medium.

If the above formula is used to solve the electromagnetic field problem, there are still great difficulties in mathematics. Therefore, the introduction of vector magnetic bit A simplifies the problem,

$$\mathrm{B} = \nabla \times \mathrm{A} \tag{3}$$

In order to guarantee the uniqueness of A, according to the Coulomb specification

(Coulomb Gauge) is：

$$\nabla \times \mathrm{A} = 0 \tag{4}$$

According to equations (1)~ (4), it can be deduced：

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathrm{A} \right) = 0 \tag{5}$$

The Maxwell equations are all in the same solution domain, such as permanent magnets, air, and magnetic walls, so equation (5) is developed in a Cartesian coordinate system, as follows,

$$\begin{cases} \frac{\partial}{\partial y}\left(\frac{1}{\mu}\right)B_z - \frac{\partial}{\partial z}\left(\frac{1}{\mu}\right)B_y - \frac{1}{\mu}\left(\nabla^2 A\right)_x = 0 \\ \frac{\partial}{\partial z}\left(\frac{1}{\mu}\right)B_x - \frac{\partial}{\partial x}\left(\frac{1}{\mu}\right)B_z - \frac{1}{\mu}\left(\nabla^2 A\right)_y = 0 \\ \frac{\partial}{\partial x}\left(\frac{1}{\mu}\right)B_y - \frac{\partial}{\partial y}\left(\frac{1}{\mu}\right)B_x - \frac{1}{\mu}\left(\nabla^2 A\right)_Z = 0 \end{cases} \tag{6}$$

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$$\begin{cases} (\nabla^2 A)_x = \dfrac{\partial^2 A_x}{\partial x^2} + \dfrac{\partial^2 A_x}{\partial y^2} + \dfrac{\partial^2 A_x}{\partial z^2} \\ (\nabla^2 A)_y = \dfrac{\partial^2 A_y}{\partial x^2} + \dfrac{\partial^2 A_y}{\partial y^2} + \dfrac{\partial^2 A_y}{\partial z^2} \\ (\nabla^2 A)_z = \dfrac{\partial^2 A_z}{\partial x^2} + \dfrac{\partial^2 A_z}{\partial y^2} + \dfrac{\partial^2 A_z}{\partial z^2} \end{cases} \tag{7}$$

In equations (6) and (7), A is the magnetic field strength; B is the magnetic induction intensity, and the adsorption force can be obtained by combining the magnetic field boundary conditions.

The adsorption force generated by the permanent magnet adsorption unit on the wall surface can be determined by the Maxwell tension method. The principle can be roughly stated as: in the homogenous medium, the adsorption resultant force F of the permanent magnet unit is equal to the area fraction of the integral of the stress tensor T at the closed surface S.

$$F = \oint_s \mathrm{T dS} = \oint_s \left[\frac{1}{\mu} (\mathrm{B} \bullet \mathrm{n}) \mathrm{B} - \frac{1}{2\mu} \mathrm{B}^2 \mathrm{n} \right] \mathrm{d}S \tag{8}$$

Where B is the magnetic flux density on the closed surface S; S is a closed curved surface in the same isotropic and medium uniform; n is the micro-unit dS outer normal unit vector; μ is the relative magnetic permeability [8, 9].

4.3 Adsorption unit coupling mode selection

Maximizing the magnetic energy utilization is to maximize the adsorption capacity of the adsorption unit and minimize the magnetic leakage generated during the adsorption process. Under a certain working gap, the larger the ratio of the adsorption force generated by the adsorption unit to the self-weight of the adsorption device, the better the adsorption result [2].

If we define

$$\lambda = \frac{F_m}{G_m} \tag{9}$$

Where the amount of adsorption force generated under a certain working air gap is the self-weight of the adsorption device.

The adsorption unit is composed of a plurality of permanent magnet units. The coupling of the adsorption device is to rationally select the spacing and overall arrangement between the individual permanent magnet units to maximize the utilization of magnetic energy, that is, to maximize the value of λ . According to existing materials, four permanent magnets are selected to be distributed on four corners of the bottom plate, as shown in Figure 4. Under the same air gap, different numbers of λ can be calculated by changing the specific values between permanent magnets. Comparing the results of calculations between different distances, the distance between two adjacent permanent magnets is selected to be set to 6 cm, and the value of λ is the largest at this time. At this time, the magnetic flux density of the adsorption device is as shown in Figure 5.

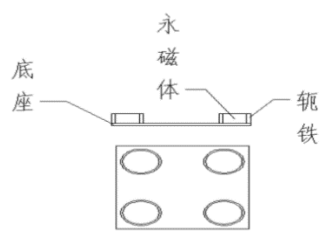

Figure 4. Structure of adsorption device

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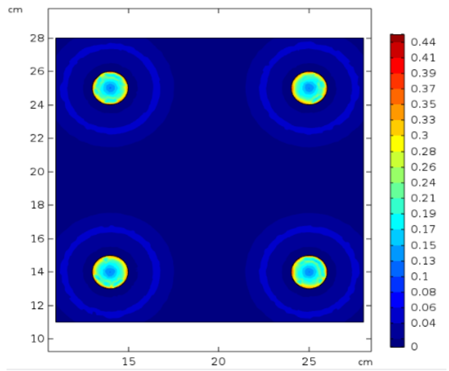

Figure 5. Magnetic flux density of adsorption device

5. Simulation results analysis

5.1 Analysis of structural parameters of magnetic adsorption

The three-dimensional model of the adsorption unit established in Comsol is shown in Figure 6. By changing one structural parameter each time and keeping other parameters unchanged, the law of the adsorption force of the adsorption unit changes with the structural parameters is analyzed. The adsorption device is composed of 4 permanent magnets and 4 yoke irons. Four of the cylindrical NdFeB permanent magnets are distributed on the four corners of a 17 cm × 17 cm aluminum square bottom plate. The distance between each permanent magnet is 6 cm. The radius of the permanent magnet is 2cm and the thickness is 1.2cm, the magnetizing direction is the thickness direction. We set the wall thickness to 13.8 mm according to actual needs. The working condition of the adjustable climbing mechanism of the wall-climbing robot is simulated by changing the gap d between the permanent magnet and the wall surface. The relationship between the air gap distance and the adsorption force when d changes from 1 mm to 7 mm is shown in Figure 7. It can be seen that as the working air gap increases, the adsorption force decreases, and as the air gap increases. The effect of the adsorption force is reduced (5mm).

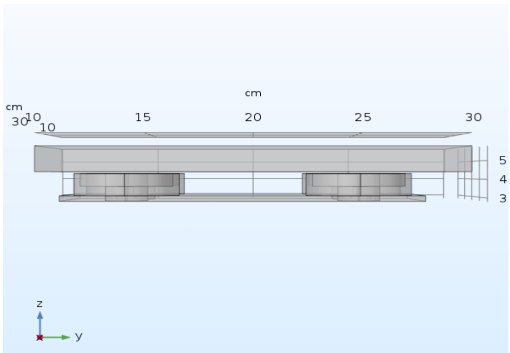

Figure 6. Model simulation 3D diagram

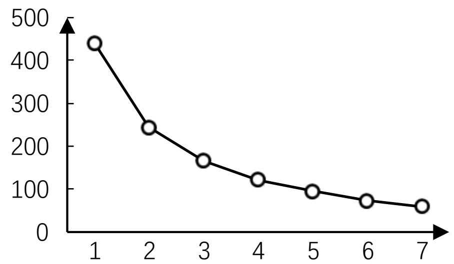

Figure 7. The change of adsorption force with gap

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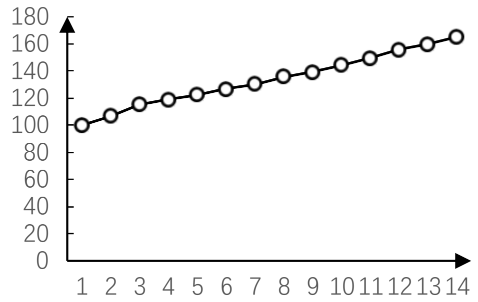

Figure 8. The change of adsorption force with wall thickness

The magnetic wall thickness is changed to simulate the robot working on different wall surfaces [11]. The air gap between the wall surface and the permanent magnet remains unchanged, and the value is set to 3mm. The change of adsorption force is calculated by changing wall thickness. The change of adsorption force with wall thickness is shown in Figure 8. It can be seen that the adsorption force generated by the adsorption device increases with the increase of wall thickness.

5.2 Magnetic adsorption structural performance test

To verify the correctness of the simulation results, the following schemes are designed to measure: four magnets are respectively installed in the upper left, lower left, upper right, and lower right positions of the permanent magnet adsorption mechanism, and the weight is measured using an electronic scale. The rope is knotted and fixed, and the circle that is knotted by the electronic scale through the rope is pierced from the middle hole, and the adsorption mechanism is slowly increased until the permanent magnet adsorption mechanism is separated from the adsorption surface, and average values are obtained after multiple measurements. After that, the ABS resin spacers of different thicknesses are measured using a vernier caliper, and the spacers are used one by one to increase the distance between the permanent magnet adsorption mechanism and the adsorption surface, and the above experiment was repeated. And we repeat the above content on a variety of different adsorption surfaces, and finally subtract the weight of the permanent magnet adsorption mechanism. The experimental results are shown in Table 2.

Table 2 Practical test table for magnetic force adsorption

distance (mm) material	1	2	3	4	5	6	7
iron plate 1 (thickness 8mm)	13.4kg	10.3kg	7.3kg	5.6kg	4.8kg	0	0
iron plate 2(thickness 13.8mm)	45.3kg	30.7kg	21.7kg	14.6kg	11.3kg	10.3kg	7.8kg
iron plate 3(thickness 16.6mm)	49.6kg	32.3kg	24.5kg	15.7kg	12.5kg	11.3kg	10.5kg

The iron plate 1 (13.8 mm) in the experiment is selected as the adsorption surface. The comparison between the results and the simulation results is shown in Figure 9. Due to the error of the measurement itself, the processing error of the processed NdFeB magnetic unit and the fragility of the permanent magnet unit surface, there is a certain error between the actual measured value and the simulation result value. However, the error fluctuation range is less than 9 percent, so it can be considered that the fluctuation is small.

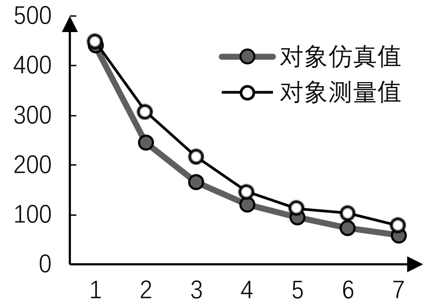

Figure 9. Comparison diagram of simulation experimental results

6. Conclusion

An adjustable permanent magnet adsorption type wall climbing robot was researched and manufactured, which involved the manufacture of the chassis and the selection of the adsorption mode and the driving method. The finite element analysis of the permanent magnet adsorption device was carried out by using Comsol software. The structure of the adsorption device was compared by calculating the adsorption force generated by the permanent magnets in different arrangement modes. The gap size and wall thickness between the permanent wall and the wall surface were studied. The effect of force is verified by comparing the actual measured data with the simulated data.

Acknowledgments

This work was supported in part by the Sichuan Science and Technology Department Application Foundation Project 2019YJ0311, in part by the State Administration of National Security under Grant sichuan-0006-2018AQ.

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