

Calculation and Analysis of The Safety of Pressure Vessel Wall Climbing Robot

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Abstract. In order to solve the problem of safety detection of pressure vessel wall, a wall climbing robot based on permanent magnetic adsorption is proposed in this paper. For climbing wall robot adsorption mechanism, from analysis of the adsorption of active permanent magnet wheel, and the statics analysis of robot's key parts and components, to find out the existing defects of the structure, the paper provides a reliable basis for robot structure optimization.

Introduction

Pressure vessel climbing wall robot is a mobile device detecting pressure vessel defect. In the working process, the adsorption of wall climbing robot on the wall needs to overcome the weight and overturning moment generated by the gravity, so whether the adsorption performance index of the adsorption mechanism meets the requirements, it is the important factor to protect the safety work of the climbing wall robot.

Robot adsorbed on the wall has always had a downward trend and a trend of overturning. These two kinds of movement trends are generated by the robot's gravity, so different forces and moments to balance are needed. The components of gravity which have a downward trend are balanced by the frictional force(F_f) between the robot and the wall, and overturning moment are balanced by the moment of adsorption force system generated by walking adsorption mechanism. The robot must meet the said equilibrium conditions to stably adsorbing on the wall. For the wall climbing robot in this project, to solve the problem of sliding and overturning, it needs to begin with the magnetic adsorption capacity and the overall structure of the robot, and improve the safety factor and the safety redundancy.

In addition, the material of the robot's components, structural rationality and processing technology are also restricting the safety of the robot. In walking, turning and detection process, the strength and stiffness of the stress parts must meet the requirements, otherwise under fatigue load, they are prone to deform and crack, causing the robot to be unable to walk normally. Therefore, the static analysis of the key parts and components of the robot and the finding of the defects in the structure provide a reliable basis for the next step of the robot structure optimization.

The adsorption force analysis of active permanent magnet wheel

The active permanent magnet wheel provides all the adsorption force(F_a) for the wall climbing robot, whose adsorption force is very important to the safety of the robot. The force on wall climbing robot is shown in Fig.1. To make the wall climbing robot be adsorbed on the wall, the following basic conditions should be satisfied:

$$\begin{cases} G \sin \alpha \leq F_f \\ F_f = \mu \cdot (F_a - G \cos \alpha) \end{cases} \quad (1)$$

$$\text{Namely: } F_a \geq \frac{G \sin \alpha}{\mu} + G \cos \alpha \quad (2)$$

Among them, μ is the friction coefficient of the permanent magnet wheel, take $\mu = 0.35$;
 α is angle between the wall surface and the horizontal;

G is the robot itself and full load weight, $G = 300N$;

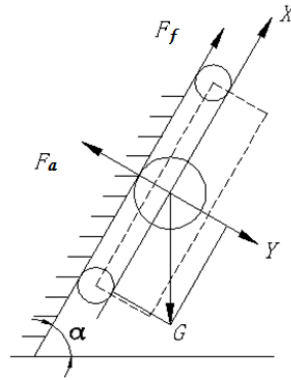


Fig. 1 Force diagram of the robot

$$\alpha = 73.3^\circ, \frac{G \sin \alpha}{\mu} + G \cos \alpha \text{ get the maximum } 897N.$$

So the adsorption capacity of the whole wall climbing robot is provided by the permanent magnet wheel.

$$F_a \geq [F]_a = 897N \quad (3)$$

The calculation of minimum adsorption capacity is the basis for the selection of the types and specifications of the permanent magnet. Among them, the selection of the magnetic material is in relation to the selection of magnet. By choosing high performance magnetic materials, it can not only meet the requirements of the robot adsorption, but can also effectively reduce the weight of the robot, and thus reduce the quality of the drive system.

The the permanent magnet chosen for this project is ring axially magnetized NdFeB rare earth permanent magnet N35, to facilitate the installation of bearings. According to the references, in the ideal state of the magnetic circuit, NdFeB permanent magnet can generate magnetic force $4.61N/cm^3$. Therefore, whether the magnetic circuit is in ideal state will be in a great extent affect the climbing wall robot's safety. But due to the boundary conditions of the magnetic flux density is difficult to determine and measure, the theoretical calculation results are not accurate enough. In view of this situation, this paper proposes using the following method to determine whether the magnetic circuit is in the ideal state, as shown in Fig.2. Compare the measured value and the simulation value of the magnetic field simulation in Gauss, to determine whether the magnetic circuit is in an ideal state.

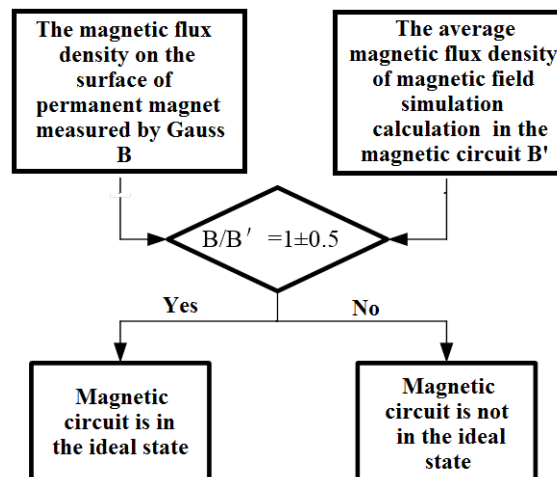


Fig. 2 The flow chat of validation of magnetic circuit

Using ANSYS simulation software to simulate the static plane magnetic field of the permanent magnetic wheel, the results are shown in Fig.3. The analysis results show that the vast majority of the ring magnet complete the cycle in the magnetic circuit, and the magnetic flux lost in the air is

very small. The maximum value of the magnetic field intensity B appears in the contact region of the yoke and the iron wall, so as to verify the rationality of magnetic circuit. Analysis shows that the average strength of the magnetic field B' in magnetic circuit is close to the numerical value of the measurement of the surface of the annular permanent magnet using the Gauss meter, and the magnetic flux density in the contact area is higher than the measured values, so we can conclude that the transfer between the magnetic energy product of ring permanent magnet to adsorption force is in the ideal state.

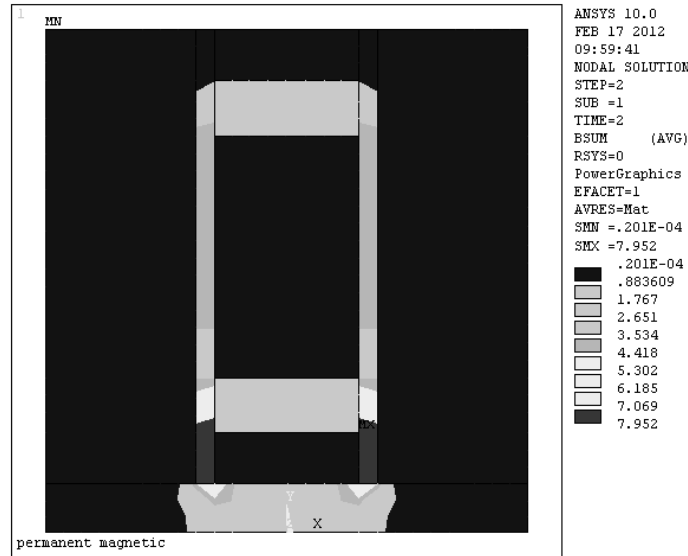


Fig. 3 The simulation diagram of magnetic flux density

According to the force analysis, the volume of the permanent magnet (V_p) of the two active permanent magnet wheels should not be less than:

$$V_p \geq \frac{1}{4.61} \times \frac{[F]_a}{2} = 97 \text{ cm}^3 \quad (4)$$

The establishment of wall climbing robot model

Robot adsorption force is mainly provided by active permanent magnet wheel. In the design of active permanent magnet wheel, theoretically, the adsorption force of the two active permanent magnet wheel should meet the demand of adsorption on the wall of the robot in the full load state in any attitude, and it should have sufficient safety factor. In order to further improve the safety redundancy of the robot adsorption on the wall, the front and rear wheels are also designed to be magnetic wheels. There are two kinds possibilities that the wall climbing robot would detach from the wall: the inefficient friction force causes the robot to slide off the wall, and the adsorption moment is not enough to cause the body to be perpendicular to the wall and overturn. Then two kinds of situation will be analyzed, to establish the robot force analysis model, as shown in Fig.4, and defined as follows:

f_n — Friction between the robot and the wall, N ;

N_1 、 N_3 — The support force of the front and rear universal wheels and the wall, N ;

N_2 — The general support of the robot, N ;

μ — The coefficient of friction between the permanent magnet wheel and the wall, $\mu = 0.35$;

α — The included angle between the wall and the horizontal plane;

G — Robot body and load weight, $G = 300N$;

F_1 — Adsorption force of universal permanent magnet wheel, N ;

F_2 — The adsorption capacity of a single active permanent magnet wheel, N ;

H ——The distance between the robot and the load of the center of gravity to the wall, $H = 0.07m$;

l ——Spacing between front and rear wheels, $l = 2 \times 0.021m = 0.042m$;

Mq ——Overturning moment, $N \cdot m$.

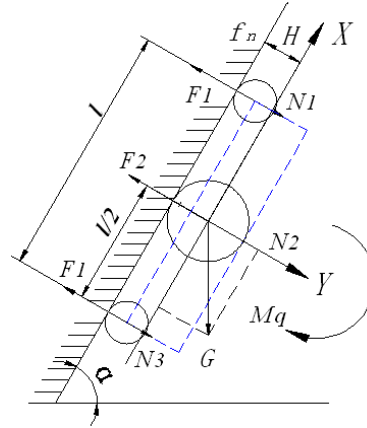


Fig. 4 The force diagram of magnetic adsorption of Wall-climbing robot

The sliding of wall climbing robot

Active permanent magnet wheel provides the adsorption force for the wall climbing robot. According to the upper section of the calculation, the adsorption force F_2 of the two active permanent magnet wheels should meet:

$$[F_2] \geq [F]_a = 897N \quad (5)$$

Take the safety factor $k=1.2$, then:

$$[F_2] \geq k[F]_a = 1076N \quad (6)$$

In this topic, the size of the ring Nd Fe B permanent magnet which is used in the active permanent magnet wheel(Outer diameter— D_o , The inner diameter— d_i) is:

$$D_o = 9cm, d_i = 5.5cm, h = 3cm \quad (7)$$

The volume of the permanent magnet is:

$$V_p = \frac{\pi}{4}(D^2 - d^2)h = 119.5cm^3 \quad (8)$$

The adsorption capacity F_2 of the two active permanent magnets is:

$$F_2 = 2 \times 4.61V_p = 1101.8N > [F_2] \quad (9)$$

Therefore, the adsorption force of the active permanent magnet wheel can meet the adsorption of the wall surface of the robot in any posture, and the adsorption of the robot will not decline.

In the usual state, two driving permanent magnet wheel can meet the requirements of the robot's adsorption on the wall stably, but to improve robot's safety redundancy, universal auxiliary wheel also uses the magnetic wheel design, the volume of the annular NdFeB permanent magnets is $15.8cm^3$. In ideal state it can generate adsorption force as:

$$F_1 = 15.8 \times 4.61N = 72.8N \quad (10)$$

The overturn of the wall climbing robot

The adsorption of the climbing wall robot concentrates on the contact line of the active permanent magnet wheel and the wall. When the adsorption force of the driving permanent magnet wheel satisfies the robot's wall adsorption, the overturning moment Mq produced by gravity G is always around the axis of the active permanent magnet wheel, namely, the center line of the robot. It can be drawn from Fig.5:

$$Mq = HG \sin \alpha \quad (11)$$

When $\alpha=90^\circ$, Mq gets the maximum value $21Nm$.

Suppose universal wheel has no adsorption force, the front and rear universal wheel, driving wheel, and chassis can form lever structure. Among them, the driving wheel and the wall surface

are fixed, the contact point between it and the wall surface is the center of rotation, as shown in Fig.5.

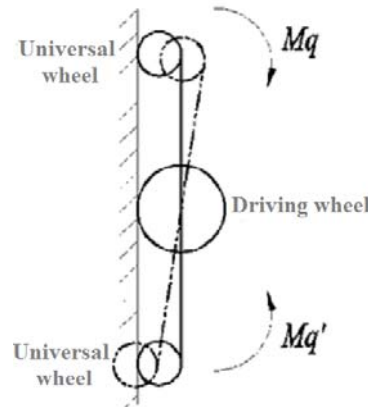


Fig. 5 The diagram of Resistive overturning

Therefore, when the strength of the premise of the chassis meet the requirements, there is always the following relationship:

$$N_3 \cdot \frac{l}{2} = -Mq = -HG \sin \alpha \quad (12)$$

And the design of universal permanent magnet wheel can make its adsorption force produce anti overturning moment.

$$Mq' = F_1 \cdot \frac{l}{2} = 15.3 Nm \quad (13)$$

The adsorption force F_1 generated by the universal permanent magnet wheel can greatly offset the overturning moment Mq , while walking adsorption structure design uses the lever principle to make the anti overturning torque transfer to the robot chassis. The adsorption force F_1 make the bending moment that the chassis bears greatly reduce, so the probability of the occurrence of capsizing is very small, which further improve safety of the wall climbing robot.

To sum up, in the case of normal walking, walking and adsorption mechanism can meet the requirement of the robot's stable and reliable crawling on the wall of any slope.

Numerical calculation and comparison of adsorption capacity

To achieve the robot's reliable adsorption on the wall surface, the condition is that the friction force F is larger than the weight of the robot W (including the weight and the load weight). F is the product of the total magnetic force $2P$ (adsorption force for a single permanent magnet wheel is P) and friction coefficient f , namely:

$$\begin{cases} F = 2fP > W \\ P > \frac{W}{2f} \end{cases} \quad (14)$$

Theoretical formula[4]

When the robot is working, magnetic lines of force generated by the permanent magnet comes into steel wall surface of permeability through the yoke, then return to the permanent magnet through the yoke to form a complete circuit.

According to the Gauss theorem $\oint \vec{B} \cdot d\vec{s} = 0$, in magnetic circuit, there are:

$$\Phi_m = \Phi_e + \Phi_l \quad (15)$$

Among them, Φ_m 、 Φ_g and Φ_l are the magnetic flux, yoke flux, and leakage flux respectively. To order:

$$\Phi_l = (k_1 - 1)\Phi_e \quad (16)$$

The formula (15) can be written as:

$$\Phi_m = k_l \Phi_e \quad (17)$$

k_l is called the flux leakage coefficient, $k_l > 1$. The formula can also be written as:

$$B_m S_m = k_l \mu_0 H_e S_e \quad (18)$$

B_m, S_m are the magnetic induction strength and cross-sectional area of the permanent magnet. H_e, S_e are the magnetic field strength and effective cross-sectional area of the yoke, μ_0 is the permeability of vacuum. In addition, according to the magnetic circuit theorem $\oint \vec{H} \cdot d\vec{l} = 0$, we can get

$$H_m L_m + H_e L_e + H_w L_w = 0 \quad (19)$$

In the formula, each item are the product of permanent magnet, yoke, magnetic field in the wall and length of magnetic path. Note that there are two times passing the yoke, and the length of magnetic path of the yoke is 2 times the length of the yoke. Suppose:

$$H_w L_w = (k_2 - 1) H_e L_e \quad (20)$$

Well, the formula(19) can be written as:

$$H_m L_m = -k_2 H_e L_e \quad (21)$$

k_2 is the coefficient of reluctance, $k_2 > 1$. It can be obtained from formula(18) and formula(21) that:

$$H_e^2 = -\frac{1}{\mu_0} \frac{1}{k_1 k_2} (BH)_m \frac{V_m}{L_e S_e} \quad (22)$$

Among them, $(BH)_m = B_m H_m$ is the product of the magnetic energy of the permanent magnet, $V_m = S_m L_m$ is the volume of permanent magnet. The larger the magnetic energy product and volume of permanent magnet are, the greater yoke magnetic field H_e is. The increase of magnetic flux leakage and magnetic resistance will make H_e decrease rapidly, and the air gap between the permanent magnetic wheel and the wall is fixed, namely, leakage magnetic coefficient k_l can be considered constant, makes H_e also dose not change.

3.2 Analysis and comparison of results

When the wall climbing robot is adsorbed on the steel wall surface, the permanent magnet wheel and the wall surface are in direct contact. Since the air gap field is not evenly distributed, the magnetic adsorption force on the contact surface of the permanent magnet wheel is:

$$F = \frac{1}{2\mu_0} \iint_S B^2 ds \quad (23)$$

In this paper, the finite element simulation method is used to generate the nodes in the region between the magnetic gaps, the total magnetic induction intensity of each node is calculated. To extract data from the ANSYS software processing, calculate the wall magnetic induction intensity after organizing the data, the formula is:

$$\bar{B} = \frac{B_1 + B_2 + \dots + B_n}{n} \quad (24)$$

The average magnetic force of the permanent magnet wheel contact surface is also available:

$$\bar{F} = \frac{F_1 + F_2 + \dots + F_n}{n} \quad (25)$$

By calculating the formula (25), the relationship curve(Fig.6) of magnetic adsorption force of the permanent magnetic wheel on the contact surface of both sides is obtained. As can be seen in the figure, the calculated values are close to the measured values, so the ANSYS simulation results are reliable. In addition, the measured value is close to the adsorption force F_2 of the active permanent magnet wheel, so the calculation of the adsorption force of the permanent magnet wheel is correct. By hanging weights, we find that even under full load condition, magnetic adsorption force is safe and reliable, and will not fall.

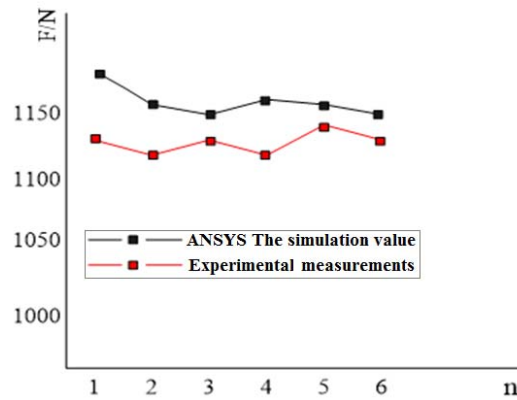


Fig .6 Comparison of the results

Structural statics analysis of key components

Force analysis of robot chassis

As the skeleton of the whole wall climbing robot, Chassis' stiffness and strength directly affect the robot's load capacity and walking ability as well as security. A power control box is needed to be placed on the chassis, which should have a certain bearing capacity. Both sides and walking adsorption mechanism are fixed. If the chassis becomes deformed under pressure, it may lead to the inconsistent walking directions of walking mechanism on both sides, and unable to achieve a straight walking line. The generated offset torque will aggravate the bending deformation of the chassis, which also makes it can not play the anti - overturning ability normally. So it is very important to analyze the force of the chassis of the wall climbing robot. When the load is applied, apply 200N downward force on the surface vertical to the frame on the position where the control box is placed, apply 40N upward force vertical to the robot in the fixed hole of each wheel shaft of the connecting running mechanism. The material is LY12 aluminum alloy. After analysis, the displacement, stress distribution diagram of the framework are respectively as shown in Fig.7, Fig.8.

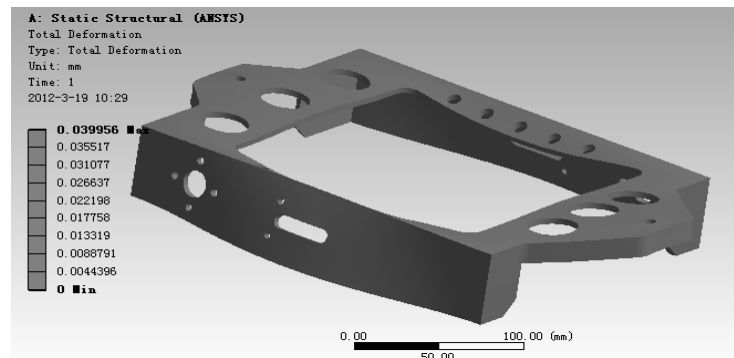


Fig. 7 The displacement distribution of chassis

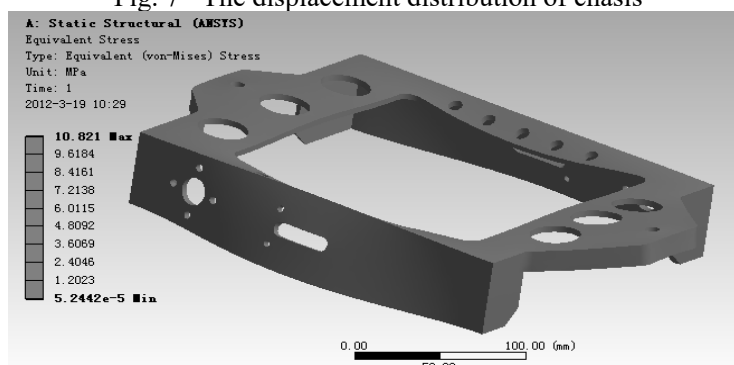


Fig. 8 The stress distribution of chassis

It can be seen from the chart, the maximum displacement deformation is 0.039956mm , the maximum stress value is 10.821Mpa . The maximum stress is at the transition of the universal wheel bending of the lower frame, but is far less than the yield limit value of the the material. At the same time, from the displacement deformation distribution graph, it can be seen, the deformation of structure is very small. Therefore, the middle frame design meet load-bearing requirements, will not cause the overall deformation and material damage. To add weight to the robot, you can reduce or remove the large circular hole designed for weight loss, and add stiffener to the beam of the lower frame.

Conclusions

Through computational mechanics analysis to the safety when the climbing robot adsorption on wall, the minimum magnetic adsorption force required to make the robot safely adsorbed to the wall, and the rationality of the design is verified. Through the finite element analysis software ANSYS, the structure statics analysis of the key parts and components of the wall climbing robot is carried out, the improvement measures are put forward, which provides a reliable basis for the safety optimization of the robot.

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