Effect of magnetic components on the smoothness of linear motion for a pedrailed wall-climbing robot

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Abstract. This paper presents the effect of the adhesion force achieved from magnetic components that are about to adhere to (off) the wall on the smoothness of linear motion for a magnetically pedrailed wall-climbing robot. This adhesion force is a kind of disturbing force, which affects the movement of the robot by affecting the torque of the sprockets. Therefore, on the basis of analyzing the limit adhesion force that ensures the robot to be adhered safely on the wall, the minimum adhesion force is determined. To calculate the adhesion force and obtain variation curve of adhesion force with the rotational angle of the sprocket, the software, Maxwell, is used to simulate the magnetic field of the magnetic components at different working positions relative to the wall, and then calculate the driving moment and resisting moment caused by magnetic components. The total moment is obtained by combing the driving moment and resisting moment by using Excel software. This total moment or torque will influence the acceleration of the robot's centroid in the walking direction. On the basis of this disturbing acceleration, the linear motion smoothness of the robot is analyzed.

1. Introduction
The wall-climbing robot can be equipped with various tools to move on the vertical wall for carrying out high-rise and difficult tasks instead of human beings in the petrochemical, energy, shipbuilding, construction and other industries in the last couple of decades [1]. The wall-climbing robot can be roughly categorized to multi-foot type, wheeled type and pedrailed type according to its adhesion mechanism [2]. The robot involved in this paper is a kind of pedrailed wall-climbing robot that can carry non-destructive testing (NDT) equipment such as portable radiographic nondestructive testing instrument and TOFD ultrasonic flaw detector moving freely on the magnetically conductive metal wall of large pressure vessels. During the nondestructive examination, the linear motion of robot with higher level of smoothness or stability is required.

Magnetic pedrailed wall-climbing robots have been developed in recent decades. Because of their large pedrail systems, stability and safety on vertical surfaces is the most important properties for these robots. The research on the safety of wall-climbing robots is reported by Xiong D, Liu Y L [3] and Zhou J X [4], and they proposed a definition of load dispersion coefficient. Based on this, a mathematical model was established, and the adhesion force of a single magnetic unit for ensuring that the robot does not turnover was obtained in their research. This dispersion coefficient method is not adopted in this article because it is difficult to measure or calculate. A kind of guideway of chains was
designed to solve the falling problem of magnetic wall-climbing robots by Lee G and Hwang K [5]. The guideway limits the movement perpendicular to the advancing direction of the pedrail links; these make a number of adhesion units working together as a whole. The adhesion force of magnetic unit studied by Zhang J Q [5], Jin S [6] And Xu Z L [7] mainly focuses on the turning movement of robots. For considering that the adhesion force has a greater influence on the flexibility of turning motion than the linear motion, therefore they ignore the influence on the linear motion. However, the robot involved in this article is used for non-destructive testing and the smoothness of its linear motion is related to the accuracy of the detection [8]. Therefore, the effects of adhesion force on linear motion are studied.

The research method of magnetic adhesion components effecting on the smoothness of robot's linear motion is the main research content in this paper. During the detecting motion of the robot, the adhesion component closest to the wall, in the front part of the pedrails, is gradually adsorbed to the wall, to give the robot a forward driving moment. At the same time, the magnetic adhesion components adsorbed on the wall at the rear part of the pedrails is gradually disengaged from the wall and forms a reversed resistance moment [9]. These two moments will both have certain influence on the smoothness of linear motion of the robot in the walking direction, and the effect will periodically change during the robot moving in a stable state. Although the curves of these two moments are periodic and stable, due to the existing of other influence factors such as links, the initial motion state and the tightness of the chain, the phase difference of the resultant moment is varied; therefore the effect of disturbing moments on the linear motion is uncertainty and will have kinds of cases. When these two moments counteract each other, the impact on movement is the least. When one of the moments is minimal and the other is maximal, there is a greatest impact on the movement. In this article, by calculating the acceleration of the moment in the linear walking direction of robot, we can roughly infer the stability of robot's motion.

2. Structure of the magnetic wall-climbing robot
The dimensions of the robot body structure are about 800× 600× 300 (mm), which with a total load of 60kg as shown in figure 1. And the magnetic unit made of permanent magnetic material NdFeB is chosen and fixed on the pedrail and is driven by two motors to walk forward, backward and turn flexibly. Each pedrail is comprised of a roller chain of 31 links respectively. Every two links has a pair of attached plates used to fix permanent magnet adhesion units, and each sprocket has 25 teeth. There are 16 adhesion components working together at the same time and each component is composed of 6 magnetic units.
3. Determination of adhesion force

In order to work out the effect of adhesion force on the movement of climbing robot, the value of adhesion force must be determined firstly. The magnetic adhesion unit provides sufficient adhesion force to determine whether a wall-climbing robot can be reliably adsorbed on the wall of a metal container.

For the wall-climbing robots, there are two types of failure: the overturning failure and the slip failure [11]. The pedrail of pedrailled wall-climbing robot is connected by hinges, so the rigidity is much poor, therefore the overall adhesion forces of pedrail cannot be calculated simply by multiplying the number of working magnetic units and the adhesion force per magnetic unit. And this is the main reason why the stability of the pedrailled robot is poor. When the robot overturns, the marginal adhesion components will be disengaged first (shown in figure 2). Therefore, when the adhesion force of the most marginal adhesion point is sufficient to ensure the whole robot does not overturn, then the wall-climbing robot is safe enough.

When the robot is adhered on the wall, the force diagram of a single pedrail is shown in figure 3. The robot is mainly subjected to gravity, magnetic adhesion force, the wall’s support force and friction [12].

In order to ensure the robot can be adhered on the wall, some conditions must be met:

1. The condition of overturning

$$\frac{G}{2}L \cos \alpha \leq LF_t$$

Where $L$ is the distance between two limit marginal adhesion points of the robot, $L$=600mm; $F_t$ is the adhesion force of single magnetic unit; $\alpha$ is the angle between the wall and the horizontal plane; $G$ is the weight of the robot with full of loads, $G$=600N.

It can be calculated, when $\alpha$=0 degree, $F_t$ = 150N.

2. The condition of slipping

$$G \sin \alpha \leq F_{friction}$$

$$F_{friction} = \mu (F_{adsorption} - G \cos \alpha) = nF_t$$

$$F_{friction} \geq \frac{G \sin \alpha}{\mu} + G \cos \alpha$$
Where $\mu$ is the friction coefficient between robot permanent magnet and steel wall of vessel, $\mu = 0.3$; $n$ is the number of magnet adhesion components working at the same time; $F_{\text{friction}}$ is friction force.

It can be obtained by calculation, when $\mu=0.3$ and $\alpha = 73.3$ degrees, $\frac{G \sin \alpha}{\mu} + G \cos \alpha$ get the maximum value which is 2088N, $F_i \geq 65.25N$.

By comparing the values of adhesion force $F_i$ under above two conditions, the determined adhesion force is more than 150N, therefore 6 cylindrical adhesion force units made of NdFeB magnet was chosen to form a magnet component to provide a 210N adhesion force. The height and diameter of the magnetic unit is 22mm and 25mm respectively, it is mounted on one chain unit match with a sprocket as shown in figure 4.

### 4. Magnetic field analysis of adhesion components

For the magnetic component that is about to disengage away from the wall, the angle and gap between the adhesion component and the wall will gradually increase as the robot moves forward[13]. This procedure of disengagement is not a simple parallel separation motion. Therefore, the NdFeB performance curve of the adhesion force with gap should be studied. In this paper, the software Maxwell is used to simulate the movement process of the adhesion (disengagement) to wall of the magnetic component, and find out the variation curve of the adhesion force of the magnetic unit.

In order to simplify the simulation calculation, only the adhesion force of one single magnetic unit is calculated. Magnetic effects between the adhesion units in a magnetic component are ignored because the gaps are much larger (38mm). Therefore the adhesion force of the magnetic component is equal to the adhesion force of the adhesion unit multiplied by the number of adhesion units in each component.

Figure 5 illustrates the magnetic induction intensity when the angle between the adhesion unit and the wall is 15 degree. And the corresponding angle of sprocket wheel is also 15 degree, and the corresponding gap between the centroid of adhesion unit and the wall is 3.54mm.

During the adhesion components disengages from the wall, the variation curve of magnetic adhesion force with the rotation angle of the sprocket is shown in figure 6 and variation curve of magnetic adhesion force with the gap is shown in figure 7.

From figure 6, it can be shown that when the sprocket angle is 0 degree, the corresponding adhesion force of the magnetic unit is 35.688N. With the angle of sprocket increasing gradually, the magnetic component is going off the wall. When the rotation angle is larger than 40 degrees, the
corresponding adhesion force of the magnetic unit is 0 N. These values are consistent with the performance values of the magnetic unit with gap as instructed by the manufacturer.

\[
M_A = \sum_{i=1}^{n} F_i \cdot l_i = \sum_{i=1}^{n} M_i \\
M_B = \sum_{j=1}^{m} F_j \cdot l_j = \sum_{j=1}^{m} M_j
\]

Where, \(n\) and \(m\) is the number of magnetic components near the front and the rear part of pedrail, \(F_i\) is the adhesion force of No. \(i\) adhesion component can provide adhesion force in the front part at the moment of gonging to engage on the wall. \(F_j\) is the adhesion force of No. \(j\) adhesion component can provide adhesion force in the rear part at the moment of gonging to disengage the wall. \(l_i\) (\(l_j\)) is the horizontal distance between the No.\(i\) (No.\(j\)) adhesion component and the axis center line of the head (rear) sprocket wheel. \(M_i\) (\(M_j\)) is driving (resistant) moment caused by front magnetic components; \(M_s\) (\(M_k\)) is resultant driving (resistant) moment caused by front magnetic components.

The disturbing moment \(M_f\) of the whole pedrail is obtained by equation (7):

\[
M_f = M_A - M_B
\]

Figure 8 shows the variation curve of moment \(M_f\) of the rear magnetic components which is going to disengage the wall. It is derived from the adhesion force in figure 6 multiplied by the number of units in a component, 6, and by the horizontal distance between the adhesion component and the center line of sprocket wheel.

It can be shown in figure 8 that the maximum moment of a single adhesion unit to the axis of sprocket wheel is 3.198Nm, and the corresponding angle of the sprocket is 14 degrees at that moment. Since the angle between two adjacent adhesion components is 28.8 degrees because there are 25 teeth in a sprocket, we transfer the same curve in figure 8 with an interval of 28.8 degrees several times, and then we get a series of curves in Figure 9.
Figure 9 shows a series moment curves of contiguous the first, second, third and fourth magnetic component with angle when the angle is between 0 degrees and 70 degrees, and it shows obvious periodicity and one period is 28.8 degrees. It can be seen that when $0^\circ < \theta < 11.2^\circ$, there are two adhesion contiguous components impacting together on the robot’s movement smoothness; when $11.2^\circ < \theta < 28.8^\circ$, only one adhesion component is closer to the wall and effects the linear movement of the robot.

By processing the curves in figure 9, the curve of the moments $M_B$ with the sprocket angle shown in figure 10 can be obtained: the values of the longitudinal coordinate of curves are superimposed, and the value of the transverse coordinate is kept constant.

For the adhesion components imminent absorbed on the wall in the front part of the robot, the gap between the adhesion component and the wall decreases with the increase of the sprocket angle, and the adhesion force increases gradually. The variation of moment $M_A$ is shown in figure 11, and its curve is symmetrical with the curve in figure 10 in shape.

By calculate the algebraic difference between the moment $M_A$ and $M_B$ at a certain position, we get the disturbing moment $M_f$ according to equation (7), and then the value of disturbing acceleration can
by got according to equation (8). We can evaluate the motion smoothness of robot based on this criterion.

The curve of disturbing moment $M_f$ with angle in figure 12 is obtained by combining the curves of $M_\theta$ in figure 10 and $M_A$ in figure 11. Firstly, transfer the curve in figure 10 to the right 14 degrees (Corresponding to the maximum moment), then subtract the corresponding curve in figure 11, and then the curve of disturbing moment $M_f$ with angle in figure 12 is obtained. It can be seen from figure 10-12, when the value of the transverse coordinate is 14 degrees, $M_\theta$ get the minimum value 0.713Nm, while $M_A$ get the maximum value 3.198Nm, and $M_f$ is 2.458Nm.

According to equation (8), when the total disturbing force from adhesion components of the robot is $2F=46.5N$, disturbing acceleration is $0.775 \, \text{m/s}^2$.

$$a_m = 2F = \frac{2M_f}{l} \quad (8)$$

$$t = \frac{2\pi \theta l}{360v} \quad (9)$$

Where $a$ is the total disturbing acceleration caused by adhesion components of the robot; $m$ is the total mass of robot; $F$ is disturbing force of magnetic components on a single pedrail of the robot; $l$ is the distance between action point of magnetic force and axis center of sprocket, equal to 105.7mm; $v$ is the scanning speed of nondestructive detection, $v=50\, \text{mm/s}$. According to equation (8) and equation (9), the curve of the variation of disturbing acceleration with time in figure 13 is obtained.

![Figure 13. Curve of disturbing acceleration with time.](image_url)

The driving power of the wall-climbing robot is provided by two Panasonic A5II series servo motors. The motor’s output power is 400W and the rated torque is 1.3 Nm. The reducer is a planetary reducer, with a reduction ratio of 60 and its rated output torque is 44Nm.

From figure 12 and figure 13, we know that the maximum disturbing moment caused by adhesion components is 5.6% of the driving torque provided by the servo motors, and it does not affect the detection work and can meet the requirement of application.

6. Conclusions
A kind of wall-climbing pedauled robot used to carry out non-destructive testing (NDT) of large pressure vessels is described. And a method of estimating the effect of magnetic components on the linear motion smoothness was proposed and studied.

On the basis of static analysis, the safe adhesion force of a single magnetic unit reasonably determined is 150N, thus the required magnetic component is determined. By using Maxwell software, the relationships of magnetic components with the gap, angle and adhesion force during the robot’s walking process are achieved.
By using Excel software, the periodic disturbing moment and acceleration on a single pedrail is simulated, and the result of study show that the disturbing moment caused by magnetic components does not affect the detection work for this wall-climbing robot.

Acknowledgments
The work was financially supported by the science and technology project of the State administration of quality supervision and inspection (No.2017QK066).

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