Analysis of the Wheel-wall Gap and Its Influence on Magnetic Force for Wheeled Wall-climbing Robot Adsorbed on the Cylindrical Tank

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***Abstract*—For the permanent magnet adsorption and four-wheel wall-climbing robot adsorbed on the surface of the cylindrical tank, only three wheels contact the wall, and one wheel is non-contact in general. The solution method of the contact point position on the contact wheels is put forward in this paper. The wheel-wall gap equation of the wheels of the robot is derived. The coordinate transformation matrix is established, which can be used to describe the position and orientation between the robot and the tank. Combined the robot parameters, the distribution curves and maximal values of the wheel-wall gaps of three contact wheels and one non-contact wheel are calculated. The influence of wheel-wall gap on the magnetic adsorption force is obtained by ANSOFT simulation. The analysis and calculation methods can be used to design the magnetic wheel and control of the wheeled wall-climbing robot.**

***Keywords*—wheeled wall-climbing robot; permanent magnet adsorption; cylindrical tank wall; wheel-wall gap**

I. INTRODUCTION

With the rapid development of science and technology, robot technology is increasingly applied to various industries to replace tedious human labor. As an important part of the field of mobile robot, wall-climbing robot integrate movement technology and adsorption technology [1], which enable the robot to crawl on vertical walls, inclined walls or tank surfaces, and carry devices to complete inspection or other tasks. Among them, the permanent magnet wheeled wall-climbing robot has a good application prospect in the tank wall detection due to its compact structure, simple control and agile motion, so many researchers have developed the permanent magnet wheeled wall-climbing robot [2~7].

For wall-climbing robots, adsorption performance is the main factor affecting its stable operation. Therefore, in the research of wall-climbing robots, the magnetic analysis and simulation will be focused. Cai et al. proposed a new type of wall-climbing robot with magnetic wheels, carried out the force analysis of the possible instability form of the robot, and then the adsorption force of the magnetic wheel was obtained by MATLAB, the magnetic simulation of the wheel was carried out by ANSOFT [8]. The paper analyzed the stability of the permanent magnet wheeled wall-climbing robot from several aspects, and carried out the stability simulation, and then the simulation curve was obtained by MATLAB, which provides the basis for the stability design of the robot [9]. Zhang developed a permanent magnet wheeled wall-climbing robot, the stability of the robot was analyzed, and ANSOFT was used to perform magnetic simulation to design and optimize the magnetic wheel [10]. In the above studies, tank walls were approximated as planes, but in the actual tank inspection, the surfaces of the tank are curved. The magnetic wheels are only in point contact with the wall. Apart from the contact point, there is a gap between the wheel and the wall, which will reduce the magnetic adsorption force.

The research object of this article is a permanent magnet wheeled wall-climbing robot with four wheels and the cylindrical tank. In order to get more accurate adsorption force that the robot stably adsorbs on the tank wall, we first need to solve the gap between the magnetic wheel and the tank wall. In this paper, we set up different coordinate systems, and use the coordinate transformation to get the coordinates of the contact points between the magnetic wheels and the tank wall, and then the distance equation is established to solve the gap. Finally, the numerical calculation was performed by MATLAB. The gaps from the magnetic wheels to the tank wall under different circumstances were obtained, and the magnetic force simulation was performed by ANSOFT to get the influence curve of magnetic force under different gaps.

II. COORDINATE DETERMINATION OF CONTACT POINTS

A. Creation of Coordinate System

First, we establish the general coordinate system C_f, which is at the bottom of the tank, the origin o_f is the center of the bottom of the tank, the direction of each coordinate axis is shown in Fig. 1. The main parameters of the tank body are the cylindrical radius *R* and the height *H*. The equations of the tank surface are as follow:

$$x_f^2 + y_f^2 = R^2 \tag{1}$$

$$0 \le z_f \le H \tag{2}$$

Next, we set up the robot coordinate system C_m, the coordinate system is established in the rectangle formed by the innermost points at the bottom of the four magnetic wheels. The origin o_m is the center of the rectangle, the direction of each coordinate axis is shown in Fig. 2, and number the wheels anticlockwise, the coordinates of the innermost points of the bottom of the wheels are $A_{im}(x_{im}, y_{im}, z_{im})$, *i*=1, 2, 3, 4.

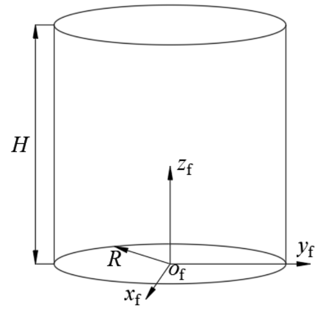

Fig. 1. General coordinate system.

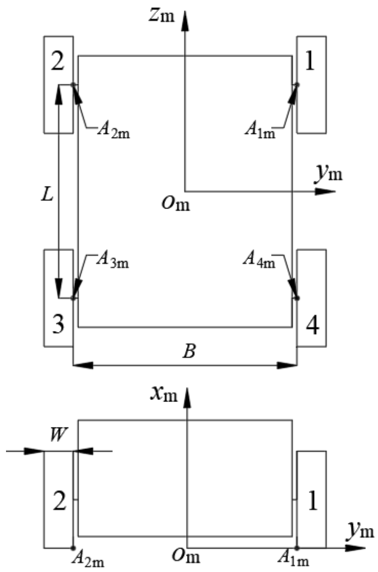

Fig. 2. Robot coordinate system.

The distance between the front and rear wheels is L, the distance between the left and right wheels is B, and the width of the wheel is W. So the coordinates of the innermost points in the robot coordinate system C_m are $A_{1m}(0,\ B/2,\ L/2)$, $A_{2m}(0,\ -B/2,\ L/2)$, $A_{3m}(0,\ -B/2,\ -L/2)$, $A_{4m}(0,\ B/2,\ -L/2)$.

B. Analysis of Contact Wheels of The Robot

The stagger angle between the positive direction of the coordinate axis z_f and z_m is represented by β. Due to the cylindrical structure of the tank, when the robot is adsorbed on the tank, only β=0, π/2, π, 3π/2, the four magnetic wheels are all adsorbed on the tank wall. In addition, the robot only has three magnetic wheels adsorbed on the tank surface, and one magnetic wheel is in the lifting state, that is, only three wheels are in contact with the tank wall. In the direction of facing the robot body, which is the opposite direction of the coordinate axis x_m, the distance from the wheel to the axis of the tank in the horizontal direction is expressed by d, as shown in Fig. 3.

When the robot has only three magnetic wheels adsorbed on the tank, under the effect of adsorption force, the distance of d is smaller, the wheel is easier to adsorbed on the cylindrical tank wall. Therefore, as shown in the figure，the two wheels that are closer to the axis of the tank in this direction will be adsorbed on the tank wall, and only one wheel of the two wheels that are far from the axis can be adsorbed on the tank wall.

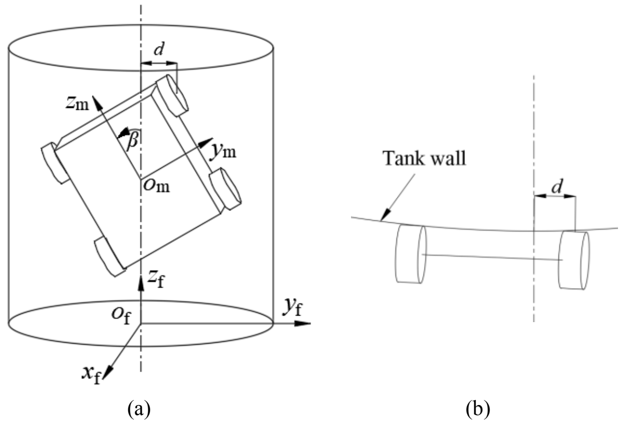

Fig. 3. The schematic diagram of the distance d.

C. Determination of Contact Points Between the Robot and the Tank Wall

In order to better analyze the contact points, the assumptions are proposed: the magnetic wheels are all approximately disks; there is no deformation when the magnetic wheels contact with the wall.

When β is in different intervals, the wheels adsorbed on the tank wall can be determined by the analysis of contact wheels of the upper part, the analysis method is the same. The paper mainly analyzes the case of $\beta \in (0,\ \pi/2)$, and solves the coordinate transformation matrix. As shown in Fig. 4, when the robot is adsorbed on the tank wall, according to the previous labeling of the wheels, at this time, wheels 1, 2, and 3 are adsorbed on the tank wall, and wheel 4 is not contact. The coordinates of the contact points between wheels 1, 2, 3 and the tank wall are represented as $A_{if}(x_{if},\ y_{if},\ z_{if})$, i=1, 2, 3.

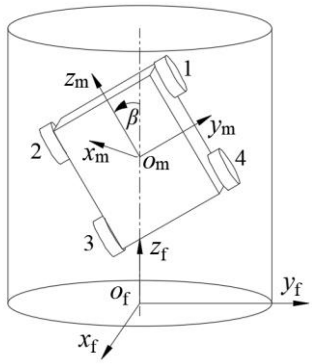

Fig. 4. Wheels 1, 2, 3 contact on the wall, wheel 4 is lifted.

Next, the coordinates of the contact points between wheel 1, 2 and 3 and the wall in the general coordinate system C_f needs to be solved. From the above, we have known that wheels 1, 2 and 3 are in contact with the tank wall, so we can select the innermost point at the bottom of wheel 1 as the first contact point A_{1f}, and the coordinate of this point just needs to meet the following conditions.

$$x_{1f}^2 + y_{1f}^2 = R^2 \quad (3)$$

$$B^2 + L^2 \le z_{1f} \le H - B^2 - L^2 \quad (4)$$

At this time, the innermost point of the bottom of wheel 2 is in contact with the tank wall, the length of the innermost points at the bottom of Wheel 1 and 2 is known, so the coordinate of A_{2f} can be solved by these conditions, the following equations must be satisfied.

$$(x_{2f} - x_{1f})^2 + (y_{2f} - y_{1f})^2 + (z_{2f} - z_{1f})^2 = B^2 \quad (5)$$

$$x_{2f}^2 + y_{2f}^2 = R^2 \quad (6)$$

Combining (5) and (6), we can get:

$$(x_{2f} - x_{1f})^2 + (\sqrt{R^2 - x_{2f}^2} - y_{1f})^2 + (z_{2f} - z_{1f})^2 = B^2 \quad (7)$$

The coordinate of A_{1f} is known, when the value of z_{2f} is determined, the value of x_{2f} can be obtained by (7), and then the coordinate of A_{2f} can be obtained. After the value of z_{2f} is determined, according to the coordinates of A_{1f} and A_{2f}, we can further determine the position and pose of the robot, and then we can get the stagger angle β. Therefore, the value of β can be obtained by the value of z_{2f}.

The contact point between wheel 3 and the tank wall is different from wheels 1 and 2. When β changes from 0 to $\pi/2$, the contact point is no longer just the innermost point at the bottom of wheel 3, the contact point will change. When β=0, the innermost point at the bottom of wheel 3 is in contact with the tank wall, with the change of β, the contact point changes from the innermost point at the bottom to the outside. Finally, the contact point is the outermost point. As space is limited, we only study the case that the innermost point of wheel 3 is in contact with the tank wall, wheels 1, 2, and 3 in this situation are all adsorbed on the tank wall at the innermost points, so the coordinate of A_{3f} can be obtained by the following conditions.

$$x_{3f}^2 + y_{3f}^2 = R^2 \quad (8)$$

$$(x_{3f} - x_{1f})^2 + (y_{3f} - y_{1f})^2 + (z_{3f} - z_{1f})^2 = B^2 + L^2 \quad (9)$$

$$(x_{3f} - x_{2f})^2 + (y_{3f} - y_{2f})^2 + (z_{3f} - z_{2f})^2 = L^2 \quad (10)$$

We need to solve the range of β when wheels 1, 2, and 3 are all in contact with the tank wall at the innermost points at the bottom. Making the line l_1 through the points A_{1f} and A_{2f}, and the line l_3 parallel to l_1 through the point A_{3f}. The line l_3 and the tank wall must intersect with two points. In addition to the point A_{3f}, there is also an intersection point is A'_{3f}, the coordinate of A'_{3f} can be expressed as $A'_{3f}(x'_{3f}, y'_{3f}, z'_{3f})$. Due to $\beta \in (0, \pi/2)$, the two intersection points must satisfy the condition $z'_{3f} > z_{3f}$, so we can use it as a basis for judgment. As can be seen from the above, the value of β can be obtained by the value of z_{2f}, so we can change the value of z_{2f} to make β changes from 0 until the above condition is not satisfied, at this time, the contact point between wheel 3 and the tank wall is no longer the innermost point at the bottom, and we can get the interval of z_{2f}.

We can get the direction vector along the positive direction of z_m in the general coordinate system based on the coordinates of A_{1f}, A_{2f} and A_{3f}, and then choose a direction vector along the positive direction of z_f. Finally, we can use the vector cosine theorem to the stagger angle β between these two direction vectors. After getting get the interval of z_{2f}, we can use it to obtain the interval of β.

III. Solution of Wheel-wall Gap

A. The Transformation Matrix of the Robot Coordinate System Relative to the General Coordinate System

The position vector of the contact points in C_m and C_f can be expressed as: $\boldsymbol{a}_i^m = [x_{im}, y_{im}, z_{im}]^T$, $\boldsymbol{a}_i^f = [x_{if}, y_{if}, z_{if}]^T$, i=1, 2, 3.

The coordinate transformation matrix of C_m relative to C_f is:

$$T = \begin{bmatrix} \boldsymbol{r}_0 & M \\ 0 & 1 \end{bmatrix} \quad (11)$$

Where $\boldsymbol{r}_0$ is the position vector of the point o_m in C_f, we can easily get $\boldsymbol{r}_0 = [\frac{x_{1f}+x_{3f}}{2}, \frac{y_{1f}+y_{3f}}{2}, \frac{z_{1f}+z_{3f}}{2}]^T$, M is the posture matrix of C_m relative to C_f.

The vector equation is as follows:

$$\boldsymbol{a}_i^f = \boldsymbol{r}_0 + M\boldsymbol{a}_i^m \quad (12)$$

Based on the coordinates of the contact points we can get the matrix M by (12).

$$M = \begin{bmatrix} \frac{\sqrt{B^2L^2 - L^2(x_{1f}-x_{2f})^2 - B^2(x_{2f}-x_{3f})^2}}{BL} & \frac{x_{1f}-x_{2f}}{B} & \frac{x_{2f}-x_{3f}}{L} \\ \frac{\sqrt{B^2L^2 - L^2(y_{1f}-y_{2f})^2 - B^2(y_{2f}-y_{3f})^2}}{BL} & \frac{y_{1f}-y_{2f}}{B} & \frac{y_{2f}-y_{3f}}{L} \\ \frac{\sqrt{B^2L^2 - L^2(z_{1f}-z_{2f})^2 - B^2(z_{2f}-z_{3f})^2}}{BL} & \frac{z_{1f}-z_{2f}}{B} & \frac{z_{2f}-z_{3f}}{L} \end{bmatrix} \quad (13)$$

Then we can get the matrix T by (11).

B. Method for Solving Wheel-wall Gap

From the above, the coordinates of the contact points in the robot coordinate system C_m can be easily obtained by the parameters of the robot, and then we can get the coordinates of the contact points in the general coordinate system C_f through the coordinate transformation matrix *T*.

These three contact points can form a plane, and the normal vector of this plane can be obtained as $\boldsymbol{n}=(a,b,c)$. The coordinate of a point at the bottom of the wheel in C_f can be expressed as $D(x_{df}, y_{df}, z_{df})$. Making a normal of the plane through this point, the intersection of this normal and the tank is *E*, then the distance between the points *D* and *E* is the gap we require. The normal equation of the plane is:

$$\frac{x_f - x_{df}}{a} = \frac{y_f - y_{df}}{b} = \frac{z_f - z_{df}}{c} \tag{14}$$

The coordinate $E(x_{ef}, y_{ef}, z_{ef})$ can be obtained by (14), and we can solve the gap by the distance equation.

$$s = \sqrt{(x_{df} - x_{ef})^2 + (y_{df} - y_{ef})^2 + (z_{df} - z_{ef})^2} \tag{15}$$

IV. Example Calculation of Wheel-wall Gap

The dimensions of the permanent magnet wheeled wall-climbing robot are designed as *B*=220mm, *L*=280mm, *W*=30mm. The dimensions of the cylindrical tank wall are set as: *R*=4000mm, *H*=8000mm. The coordinates of the innermost points at the bottom of the four magnetic wheels in C_m can be obtained by the dimensions of the robot, which are A_{1m} (0, 110, 140), A_{2m} (0, -110, 140), A_{3m} (0, -110, -140), A_{4m} (0, 110, -140).

Next, we use the above method to solve the coordinates of the contact points in C_f . The first step is to select the coordinate of contact point A_{1f} between wheel 1 and tank wall as (4000, 0, 3000) by (3) and (4). In the case of $\beta \in (0, \pi/2)$, the interval of z_{2f} is (3000, 2780), after determining the value of z_{2f} , we can get the coordinate of the contact point A_{2f} by (5) and (6). We also need to determine the value range of β, when wheels 1, 2, and 3 are all adsorbed on the tank wall with the innermost point. Based on the above judgement, it can be calculated by MATLAB that when wheels 1, 2, and 3 are all adsorbed on the tank wall at the innermost side, the interval of z_{2f} is (3000, 2920], and then we can get the stagger angle $\beta \in (0, 21.3°]$. Finally, we can get the coordinate of the contact point A_{3f} by (8), (9), (10).

We assume that when β=10°, and we can get the coordinates of contact points of wheel 1, 2, 3 are A_{1f} (4000, 0, 3000), A_{2f} (3994.13, -216.58, 2961.81), A_{3f} (3996.47, -168.01, 2686.06), the curves of the gaps between the magnetic wheels and the tank wall along the width direction of the magnetic wheel are shown in Fig. 5.

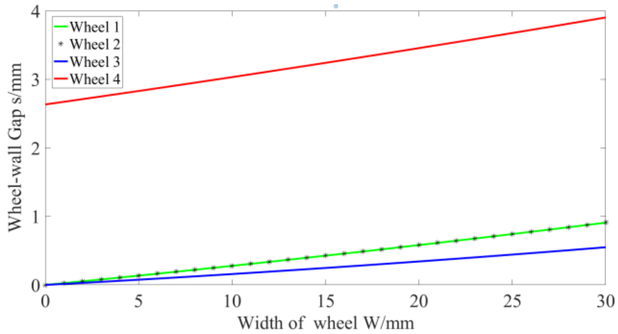

Fig. 5. Wheel-wall gap along the width direction.

As shown in Fig. 5, the gap from wheel 1 and 2 to the tank wall is almost identical, and the maximum is 0.91mm, the gap between wheel 3 and the tank wall is a little smaller, and the maximum is 0.55mm. Due to the lifting state of wheel 4, the gap is larger, the maximum is 3.9mm, which is several times of the contact wheels. From the figure we can get the change law of wheel-wall gap along the width direction of the wheel from the inside to the outside, which gradually increases and tends to linear change. This can be used for future analysis to build more accurate models.

It has been calculated that when the wheels 1, 2 and 3 are adsorbed on the tank wall with the innermost point at the bottom, the interval of β is [0, 21.3°]. From the above, we can know that the gap between the outermost at the bottom of the magetic wheel and the tank wall is the largest. Next, we get the change of the maximum gap between each magnetic wheel and the tank wall in this interval, as shown in Fig. 6.

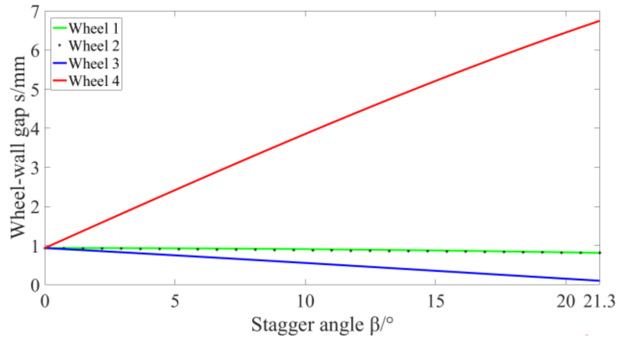

Fig. 6. Maximum wheel-wall gap in different postures.

It can be seen from the figure, when β=0°, the four magnetic wheels are all adsorbed on the tank wall, the gaps are all 0.938mm. For the contact wheels 1, 2 and 3, the gap is the largest at β=0°, when β changes from 0° to 27.4°, the gaps are all decreasing gradually, and the decreasing speed of wheel 1 and 2 is basically same, while the decreasing speed of wheel 3 is faster. The gap between wheel 4 and the tank wall is different, with the change of β, the gap is increasing until β=21.3°, the gap is the maximum, which is 6.75mm. It can be seen from the data, the gap between the non-contact wheel and the tank wall is much larger than the gaps between contact wheels and the tank wall. So the influence of wheel-wall gap on the non-contact wheel is greater during the change of the posture of the robot.

V. Magnetic Simulation Under Different Gaps

From the upper part, we get the value of wheel-wall gap of each magnetic wheel when the robot adsorbed on the tank wall with the innermost points at the bottom of contact wheels. The maximum gap of the contact wheels is 0.938mm, and the maximum gap of the non-contact wheel is 6.75mm. After getting the value of wheel-wall gap, we use ANSOFT to perform magnetic simulation, as shown in Fig. 7. The magnetic wheel is composed of permanent magnets and yoke iron alternately arranged. The diameter of the yoke iron is 100mm, the width of the yoke iron at two ends is 5mm, and the width of the middle yoke iron is 4mm. The diameter of the permanent magnet is 98mm, and the width is 8mm. The width of the magnetic wheel is 30mm, and the thickness of the wall is 10mm.

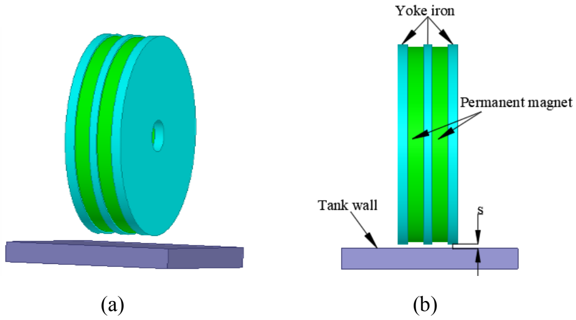

Fig. 7. The model of magnetic simulation

By changing the value of wheel-wall gap, we get the curve of the influence of wheel-wall gap on the magnetic adsorption force, as shown in Fig. 8. Wheel-wall gap increases from 0 to the maximum value of 6.75mm.

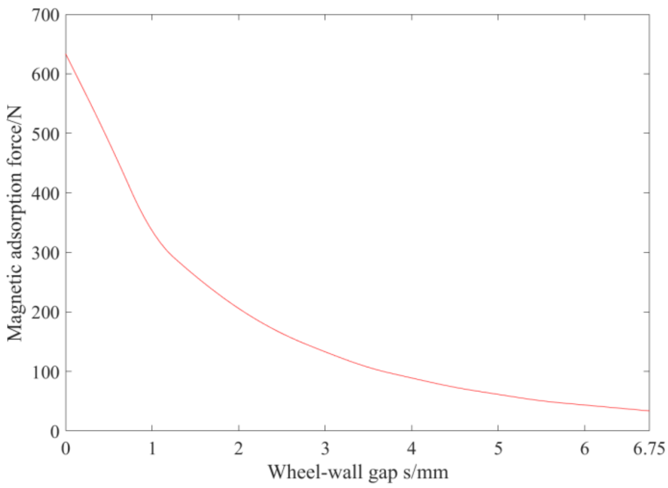

Fig. 8. Relationship between wheel-wall gap and magnetic adsorption force

As shown in Fig. 8, with the increases of wheel-wall gap from 0 to 6.75mm, the magnetic adsorption force decreases from 633.8N to 33.8N. It can be seen that the gap has a great influence on the magnetic adsorption force, so in order to obtain the more accurate magnetic adsorption force, it is necessary to solve the wheel-wall gap.

VI. Conclusion

This paper proposed a method to calculate the wheel-wall gap when the permanent magnet wheeled wall-climbing robot is adsorbed on the tank wall. Then we use the method to calculate the value of the gaps between the magnetic wheels and the tank wall by MATLAB, and obtain the change law of wheel-wall gap under different situations. Along the width direction of the wheels from inside to outside, the gaps between the wheels and the tank wall gradually increases and tend to linear change. When the robot is adsorbed on the tank wall with the innermost points at the bottom of the contact wheels, with the increases of the stagger angle β, the gaps of the contacts gradually decrease, while the gap of the non-contact gradually increases, and the increase speed is fast. In the end, we perform the magnetic simulation by ANSFOT based on the value of the gap, and get the influence curve of the gap on the magnetic absorption force. With the increase of the gap, the magnetic adsorption force will decrease exponentially, so it is necessary to solve the wheel-wall gap for the more accurate magnetic adsorption force.

The calculation method of wheel-wall gap studied in this paper can provide evidence for establishing a more accurate model for magnetic force analysis and simulation. And we can get the more reliable magnetic adsorption force, which is of great significance for the robot to work safely and stably on the tank wall.

References

[1] Yan J, Zhao X, Zuo G, et al. Research Status and Analysis of Technology Application for Wall-Climbing Robot[J]. Mechanical Research & Application, 2015 (3): 18. (in Chinese)

[2] Fei Y, Zhao X, Wan J. Motion analysis of a modular inspection robot with magnetic wheels[C]//2006 6th World Congress on Intelligent Control and Automation. IEEE, 2006, 2: 8187-8190.

[3] Fischer W, Tâche F, Siegwart R. Magnetic wall climbing robot for thin surfaces with specific obstacles[C]//Field and Service Robotics. Springer, Berlin, Heidelberg, 2008: 551-561.

[4] Zhang D, Chen J, Li Z. An omni-directional wall-climbing microrobot with permanent-magnetic wheels actuated by electromagnetic micromotors[J]. Robot, 2011 (6): 12.

[5] Okamoto J, Grassi V, Amaral P F S, et al. Development of an Autonomous Robot for Gas Storage Spheres Inspection[J]. Journal of Intelligent & Robotic Systems, 2012, 66(1-2): 23-35.

[6] Cho C S, Kim J D, Lee S G, et al. A study on automated mobile painting robot with permanent magnet wheels for outer plate of ship[C]//IEEE ISR 2013. IEEE, 2013: 1-4.

[7] Espinoza R V, de Oliveira A S, de Arruda L V R, et al. Navigation's stabilization system of a magnetic adherence-based climbing robot[J]. Journal of Intelligent & Robotic Systems, 2015, 78(1): 65-81.

[8] Cai J, He K, Fang H, et al. The design of permanent-magnetic wheeled wall-climbing robot[C]//2017 IEEE International Conference on Information and Automation (ICIA). IEEE, 2017: 604-608.

[9] Liu J, Tang D, Jia P. Stability Analysis of Wheeled Ultrasonic Testing Climbing Robot [J]. Machine Design and Research, 2016, 32(5): 25-30. (in Chinese)

[10] Zhang X. Research on Wall-Climbing Robot of Wheel-Shaped Suspended Magnetic Adsorption [D]. Harbin Institute of Technology, 2012, 2. (in Chinese)