Design and adsorption force optimization analysis of TOFD-based weld inspection robot

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Abstract. To meet the requirements of large metal tank weld inspection, a robot design scheme was proposed to walk on the outer surface of the tank and carry TOFD probe. The wall-climbing module, connecting frame module and TOFD weld inspection module are specifically designed. In this paper, the permanent magnetic adsorption principle and four-wheeled mechanism are both adopted in the wall-climbing module, meanwhile, the magnetic wheel's adsorption force is analyzed under multiple parameters. The main parameters affecting the adsorption force are obtained. To ensure the minimum size and the lightest quality of magnetic wheel, the adsorption force is also optimized based on the main parameters which are related to the permanent magnet itself. The above work provides a reference value for the research and development of intelligent weld inspection products of large metal tanks.

1. Introduction

Large metal tank is an important infrastructure of oil, gas, chemical and other industries, which plays an irreplaceable role in industrial production. This kind of tank is generally made of many pieces of sheet steel under welded. Taking vertical cylindrical tank and vertical spherical tank as an example, a large number of welds are evenly distributed on the apparent surface. It will lead to leakage, explosion, fire and other serious safety accidents once cracks, corrosion and other problems appeared on the welds. The traditional method of weld flaw detection needs to detect defects and thus help ensuring functional safety of the structure. With the help of scaffolding, inspectors carry detection instruments close to different positions on the surface of the tank for manual operation, as shown in Figure 1. This manual inspection method has common disadvantages, such as low efficiency, high cost, potential safety hazard and low degree of automation. Therefore, there is an urgent need to design a robot that can replace the manual completion of large metal tank weld inspection.

At present, the research on intelligent operating equipment for metal surface mainly focuses on the wall-climbing robot (WCR), which carries different tools to polish, clean and inspect the metal surface. In 2008, Shang J, Bridge B, Sattar T P et al. developed a robot (named “NDT Robot”) for testing the weld quality on the hull surface [1], which adopted wheeled locomotion and permanent magnetic adsorption, and a series of permanent magnets were installed on the bottom plate of each vehicle body as a non-contact adsorption device. In 2010, Raul Fernandez et al. developed a prototype robot for autonomous tank detection. There was a disc in the middle of the magnetic wheel which was made of non-magnetic nylon material. And twelve through-holes, which were filled with 12 cylindrical
permanent magnets, were evenly distributed in the original disc. Two cylindrical yoke irons were distributed on both sides of magnetic wheel. Three o-shaped rubber rings were outside the original disc to increase the friction between the wheels and the wall surface [2]. In the robot developed by Eich M et al. in 2011 for hull detection, the structure small cylindrical permanent magnets uniformly installed along the outer circumference of the magnetic wheel. The axes of permanent magnetic and magnetic wheel were perpendicular. The permanent magnets were adsorbed alternately on the wall surface during the locomotion of the robot [3]. A flexible wall and ceiling climbing robot with six permanent magnetic wheels was proposed in 2015 by Zhang Y, Dodd T, Atallah K, et al. The body was divided three parts. Each of them was connected with flexible joint mechanisms so that the body could accomplish bending motions. Besides, four universal joints were coupled to the drive wheels and two spherical bearings were used to fix the middle casters to achieve wheel bending motions [4]. A new type of crawler-type magnetic adsorption wall-climbing robot for derusting of ships was designed in 2017 by Hu S, Peng R, He K, et al. The magnetic circuit consisted of two permanent magnets, yokes and magnetic plates, which could provide enough adsorption force to overcome two common overturning risks [5]. One novel type of robot was proposed, which could climb on different structural shapes and transited from one surface to another. The tank-like robot was designed with reciprocating mechanism and roller-chains which made both sides of tracks could be relatively rotated to fit with tanks with different radius of curvature [6]. A magnetic climbing robot to perform autonomous welding in the shipbuilding industry was developed by Kermorgant in 2018. The robot was able to carry 100kg payload with two magnetic tracks and a 2D laser scanner was equipped to deliver hull surface’s information. Two-degree of freedom’s arm with welding torch could realize welding process [7].

To sum up, the above developed robots are either both complex and bulky in structure or low in practicability of adsorption principle, which makes it difficult for the robot to achieve engineering application, especially the lack of corresponding product research and development in the intelligent inspection devices of welding seams of large metal tanks. Therefore, this paper firstly designed a robot that moved flexibly on the surface of large metal tanks and was equipped with TOFD probe to realize welding seam inspection. Secondly, the main parameters of the simple and effective adsorption device were designed, the adsorption force under different parameters were analyzed, optimized and verified by experiments.

![Figure 1. Manual inspection of welds on the large metal tanks.](image)

2. **Overall design of TOFD-based weld inspection robot**

The surface area of large metal cans is generally more than 100m². In addition to the distribution of welding seams, the curvature of the outer surface is almost flat. Therefore, the requirements for the whole robot are mainly reflected in the following aspects: high detection accuracy, reliable adsorption
and strong modularity. In this paper, the design scheme of welding seam inspection robot as shown in Figure 2. The physical prototype of the whole robot is shown in Figure 3.

**Figure 2.** The 3D model of TOFD-based weld inspection robot.
1-WWM 2-CFM 3-WFDM 4-Welds 5-Tank

**Figure 3.** The physical prototype of TOFD-based weld inspection robot.

As the carrying platform, the wall walking module (WWM) 1 adopts the permanent magnet wheel adsorption and four-wheel locomotion, which are driven by two MAXSON DC motors and corresponding planetary reducers. The synchronous toothed belt transmission is accepted to realize the linkage of front and rear wheels on the same side, which reduce the turning radius and improve the walking flexibility. It’s capable of carrying 15kg load capacity. The entire WWM is composed of various parts as shown in Figure 4(a).

Many welds are regularly distributed on the outer surface of large metal tanks with certain heights (3mm–5mm) and there will be a cross welds situation (as shown in Figure 2). The connection frame module (CFM) 2 can ensure that the TOFD WFDM is pressed tightly on the wall surface and has certain adaptive ability in the process of crossing the welds. It’s composed of two sets of four-bar mechanism as shown in Figure 4(b).

TOFD (time of flight diffraction technique) was first proposed by Dr. Silk and his team from Harwell nondestructive testing laboratory in the UK in the 1970s. After nearly half a century of development, it has been widely used in the welding quality inspection of pressure pipelines, oil storage tanks, nuclear industry and automobiles [8, 9]. In this work, TOFD weld flaw detection module (WFDM) 3 is shown in Figure 4(c). It’s composed of a pair of p-wave oblique probe (one receiving and one sending) which are located on both sides of the welds. The preset distance (δ) between the two probes can be adjusted by moving No.2 along No.1 to accommodate to different width, depth and height of the weld. Besides, the water is transferred to 3-1 through water pump and water pipe on the ground to realize water coupling.

3. **The design of adsorption device**

As the core part of the whole robot, the performance of adsorption device directly influences the reliability, flexibility and carrying capacity of the operating system. This design of the adsorption device uses magnetic wheels, which combines the locomotion and adsorption into one and simplifies the structure of the robot body.

In this section, cylindrical magnetic wheel shape and permanent magnet Halbach array principle [10, 11] are fused together to design a type of magnetic wheel with simple structure and strong engineering application. As shown in Figure 5, the magnetic wheel is made up of cylindrical yoke iron - permanent magnet - yoke iron - permanent magnet - yoke iron in sequence. The outer surface is covered with a layer of rubber to increase the friction between the magnetic wheel and the wall surface as well as prevent scratching the wall surface during the locomotion. The permanent magnet is made of brittle materials and can’t be used for driving torque. Therefore, the permanent magnet is provided with a through hole with a diameter larger than the drive shaft diameter.
Figure 4. The concrete design of TOFD-based weld inspection robot.

Figure 5. Magnetic wheel structure and section diagram.
4. The simulated analysis and optimization of magnetic wheel adsorption force based on Ansoft Maxwell Software

4.1. The definition of analysis parameters and material
Ansoft Maxwell (ASM) software has been widely accepted for engineering electromagnetic analysis. In this section, it’s used to analyse the magnetic field and adsorption force of the magnetic wheel. Under the condition of meeting the requirements of the adsorption force, then the wheel structure will be optimized to ensure the overall size of it reached the minimum so that the its quality was the lightest. The characteristics of magnetic wheel model are simple and high-spatial symmetry, so 2D magnetic field analysis module is adopted to analyse its simplified model, the parameters are shown in Figure 6.

After mechanical analysing to keep the whole robot away from slipping and overturning, the analysis objective was defined: the adsorption force generated by a single magnetic wheel on the wall surface is $F_{m0} = 200N$. So the sum force of the four magnetic wheels is 800N. The initial analysis parameters of the magnetic wheel are set as shown in Table 1.

![Figure 6. Dimension parameters of magnetic wheel.](image)

Table 1. Definition of dimension parameters and material properties.

| Name               | Material | Definition            | Dimension                      |
|--------------------|----------|-----------------------|-------------------------------|
| Tank wall          | Q235     | B-H curve             | T=4mm L=100mm                 |
| Permanent magnet   | Marks:N  | Shown in Table 2.     | $\phi 3 = 74mm \ \phi 4 = 20mm$ |
| Yoke iron          | 45# steel| B-H curve             | $\phi 2 = 78mm \ T1 = 4mm \ T3 = 3mm$ |
| Air                | $/\mu_r = 1.0$ | $\delta=0~10mm$ | Rectangular region:200mm × 200mm |
| Rim rubber         | HNBR     | $\mu_r = 0.99990$    | $\delta_1 = 82mm$            |
| Drive shaft        | 6061A    | $\mu_r = 1.000022$   | $K \times K = 8mm \times 8mm$ |

Where: $\mu_r$ - Relative permeability; HNBR- Hydrogenated Nitrile Butadiene Rubber; AL-Aluminum alloy.

As can be seen from the Table 1, rim rubber and drive shaft are made of materials with low magnetic conductivity, so they can be equivalently defined as air in the analysis.
Table 2. Performances and parameters of N35.

| Items     | Typical value |
|-----------|---------------|
| Br(T)     | 1.21          |
| BHC(kA/m) | 890           |
| MHC(kA/m) | 1090          |
| (BH)max(kJ/m³) | 278         |

4.2. The relationship between the air gap height ($\delta$) and adsorption force ($F_m$)

In the process of locomotion, it’s difficult to ensure that the magnetic wheel is always close to the wall, when the welding seam is encountered, the wheel will be lifted, which increases the air gap height. Because of the air permeability is very low, this will make the adsorption sharply decreased. Therefore, it’s necessary to study the relationship between the air gap height $\delta$ and the adsorption force $F_m$ to ensure that $F_m$ does not change abruptly when crossing the welding seam. In the whole analysis process, the 2D model of magnetic wheel in ASM is shown in Figure 7.

![DOM-Direction of magnetization](image)

**Figure 7.** The 2D model of magnetic wheel in ASM ($\delta = 5\text{mm}$).

It can be seen from the cloud chart of magnetic flux density in Figure 8 that when two permanent magnets are magnetized in opposite directions, their magnetic flux lines appear superposition phenomenon inside the wall surface to enhance the adsorption force and improve the utilization rate of magnetic energy.

When there is no obstacle on the wall ($\delta = 0\text{mm}$), the rubber edge is in direct contact with the wall. The analysis was conducted by successively increasing the air gap height 0.5mm until the maximum height ($\delta = 10\text{mm}$). The result is shown in Figure 9.

As can be seen from Figure 9, the adsorption force ($F_m$) decreases exponentially with the increase of air gap height ($\delta$).

1. When $\delta \in (1.5,2.5)$, $F_m$ decreases sharply.
2. When $\delta \geq 6.5, F_m < 200$ which can’t meet the requirement.

Therefore, the gap height safety range is $\delta \in (2.5,6)$. The welding seam height on the surface of large metal tanks is generally between 3mm and 5mm, which is within the safe range. Thus, if the robot encounters obstacles with a height greater than 6mm during the locomotion, the operator needs to carry out additional human intervention to prevent the robot from falling.
Figure 8. The cloud chart of magnetic flux density (Mag_B) of magnetic wheel ($\delta = 5\text{mm}$).

Figure 9. The relationship between $\delta$ and $F_m$. 
4.3. The relationship between the thickness of side yoke iron \((T_1)\) and adsorption force \((F_m)\)

The two side-yoke irons are located at the N extreme of the permanent magnets. The yoke irons are made of soft iron with high magnetic conductivity. Most of the flux lines generated by the N pole are transmitted to the steel wall surface through the yoke iron on both sides and a small part of them are attenuated in the air. Therefore, the thickness \((T_1)\) will affect the effect of magnetic field transmission and attenuation. The initial definition of thickness \(T_1 = 4\text{mm}\), the analysis result is shown in Figure 10 by changing the value of \(T_1\) with other parameters unchanged.

![Figure 10. The relationship between \(T_1\) and \(F_m\).](image)

As can be seen from Figure 10, with the increase of \(T_1\), \(F_m\) increases linearly. Take \(\delta = 5\text{mm}\) as example.

(1) When \(T_1 \in (1,3)\), the linear coefficient \(K \approx 11.3\), \(F_m\) increases significantly. However, the yoke iron is too thin so that it’s difficult to ensure the strength in the process of transferring torque when connected to the drive shaft.

(2) When \(T_1 \in (4,6)\), the linear coefficient \(K \approx 8.5\), \(F_m\) increases steadily and the yoke iron thickness was moderate and adjustable.

(3) When \(T_1 \in (7,10)\), the linear coefficient \(K \approx 7.0\). At this time, the increase of \(T_1\) has a low influence on \(F_m\) but inversely increase the weight of the whole magnetic wheel. Therefore, the ideal range of \(T_1\) is \(T_1 \in (4,6)\).

![Figure 11. The relationship between \(T_2\) and \(F_m\).](image)
4.4. The relationship between the thickness of permanent magnet \( (T_2) \) and adsorption force \( (F_m) \)

As the source of \( F_m \), the size parameter of permanent magnet itself will affect \( F_m \). \( T_2 = 6 \text{mm} \) was initially defined, the analysis result is shown in Figure 11 by changing the value of \( T_1 \) with other parameters unchanged.

As can be seen from Figure 11, with the increase of \( T_1 \), \( F_m \) increases exponentially. Take \( \delta = 5 \text{mm} \) as example.

(1) When \( T_2 \in (1,4) \), the thickness of the permanent magnet is too thin and \( F_m \) is very small, so it’s difficult to meet the requirements.

(2) When \( T_2 \in (5,7) \), \( F_m \) is suitable, which can not only meet the adsorption requirements but has an adjustable range to be optimized.

(3) When \( T_2 \in (8,10) \), \( F_m \gg F_{m_0} \), which can’t meet the requirements.

Therefore, from the perspective of lightweight, the ideal value range of permanent magnet thickness \( T_2 \) is \( T_2 \in (5,7) \).

4.5. The relationship between the internal hole diameter of permanent magnet \( (\phi4) \) and adsorption force \( (F_m) \)

As mentioned above, a certain size of through-hole is opened in the permanent magnet to avoid fracture failure due to direct connection with the drive shaft. On the other hand, the changing of \( \phi4 \) is able to adjust \( F_m \). Now, we can change the \( \phi4 \) \( (K - 2 \leq \phi4 \leq 03 - 2, K \) is the size of the drive shaft shown in Figure 6. and its value is shown in Table 1) numerical to analyze \( F_m \) and observe the relationship between them, the result is shown in Figure 12.

![Figure 12. The relationship between \( \phi4 \) and \( F_m \).](image)

As can be seen from Figure 12, with the increase of \( \phi4 \), \( F_m \) decreases gradually. When \( \phi4 \) changes closely to the outer diameter of the permanent magnet, \( F_m \) changes sharply. On the contrary, \( \phi4 \) is too large and the effective section of permanent magnet is too small. So, the adsorption stability is poor.

Take \( \delta = 5 \text{mm} \) as example.

(1) When \( \phi4 \in (10,30) \), the internal hole diameter is too small and \( F_m > F_{m_0} \), so \( F_m \) is surplus.

(2) When \( \phi4 \in (30,50) \), \( F_m \) is both close to \( F_{m_0} \) and slightly larger than it, which can ensure reliable adsorption and a certain range of adjustment.

(3) When \( \phi4 \in (50,72) \), \( F_m \) is less than \( F_{m_0} \). So it can’t meet the requirements.

Therefore, the ideal value of the internal hole diameter \( \phi4 \) is \( \phi4 \in (30,50) \).
4.6. The adsorption force optimization analysis

Based on the above analysis, taking the influence degree of a certain parameter on $F_m$ (other parameters within a reasonable range) into consideration, it can be seen that $\delta$ is the biggest factor. But its value is determined by the working environment, which is difficult to be manually controlled. From the perspective of security, the maximum value $\delta = 5\text{mm}$ is considered during analysing. Comparatively speaking, $T_1$ has the smallest influence on $F_m$. On the basis of ensuring that its thickness is enough to transmit flux line and meet the requirement of transmission strength, the smaller the value is, the more favourable it’s to reduce the weight of magnetic wheel. The two parameters of permanent magnet itself ($T_2$ and $\Phi 4$) are decisive role to the $F_m$. Hence, the multi-parametric analysis is carried out by adjusting the values of $T_2$ and $\Phi 4$ at the same time. The optimization analysis parameters were defined as shown in Table 3 and other no mentioned parameters are the same with Table 1.

| Name          | Dimension               |
|---------------|-------------------------|
| Permanent magnet | $\delta = 74\text{mm}$ |
|               | $\Phi 4 \in (30,50)$, Step: 2mm |
|               | $T_2 \in (5,7)$, Step: 1mm |
| Yoke iron     | $\Phi 2 = 78\text{mm}$ |
|               | $T_1 = 4\text{mm}$, $T_3 = 3\text{mm}$ |
|               | $\delta = 5\text{mm}$ |
| Air           | Rectangular region: $200\text{mm} \times 200\text{mm}$ |

Based on the above bivariate simulation analysis, the analysis results are obtained shown in Figure 13.

![Figure 13](image)

**Figure 13.** The relation between the two parameters ($T_2$ and $\Phi 4$) and $F_m$.

It can be easily found from Figure 13 that the change of $\Phi 4$ value, within the error range, contributes to access the ideal adsorption force $F_{m0} = 200\text{N}$ when keeping $T_2 = 6\text{mm}$.

4.7. The experimental verification of adsorption device

In order to verify the above results, three magnetic wheels were processed in this work and adsorption force experiments were carried out on $T = 4\text{mm}$ Q235 steel plate surface with the help of a puller as shown in Figure 14. The surface is untreated which is closer to the polished wall surface. The measured adsorption force was shown in Table 4.
**Figure 14.** The measurement of magnetic wheel adsorption force.

**Table 4.** The comparison between simulated results and experimental results of adsorption force ($T_2 = 6\text{mm}$).

| $\Phi 4/\text{mm}$ | 42   | 44   | 46   |
|-------------------|------|------|------|
| **Simulated: $F_m/N$** | 214.9 | 204.0 | 191.5 |
| **Experimental: $F^*_m/N$** | 232.2 | 218.4 | 203.8 |
| **Relative error: $e_r/\%$** | -7.45 | -6.59 | -6.04 |

Where: $e_r = \frac{F_m - F^*_m}{F^*_m} \times 100\%$

Overall, the relative error between the experimental results and the simulated results is within 8%. So, the simulation results can be used to guide the design of magnetic wheel. It means that the expected adsorption force ($F_m$) can be acquired by changing the $\Phi 4$ and $T_2$ when the magnetic wheels is adopted as adsorption device.

**5. Conclusions**

This paper presents a robot that can replace the manual inspection of welding seams on the external surface of large metal tanks. The WWM adopted the four magnetic wheels, which integrated the adsorption device with the locomotion. The relationships between the adsorption force and several major parameters were analysed in detail when magnetic wheel was used as the adsorption device. The ideal range of each parameter was given. In addition, one innovative method was proposed to adjust permanent magnet adsorption by changing the internal hole diameter of permanent magnet ($\Phi 4$). To ensure the overall size of magnetic wheel reached the minimum and the quality was the lightest, the optimization analysis was carried out based on the two main parameters ($\Phi 4$ and $T_2$) under the condition of meeting the requirements of the adsorption force. The comparison between simulated results and experimental results of adsorption force shows that this method can acquire the expected adsorption force within a certain error tolerance.

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