Design and Simulation of ROV Wheel Electromagnetic Adsorption Structure

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Abstract. This paper investigates the wheeled magnetic adsorption structure of a remotely operated underwater vehicle (ROV), with the objective of replacing manual labor in the inspection of underwater ferromagnetic surfaces. It integrates wheeled wall-climbing technology and electromagnetic adsorption to ensure stable adhesion on various wall geometries. The propulsion system employs differential motors driving rubber wheels, utilizing a variable-diameter walking mechanism to adapt to different wall profiles. Additionally, a comprehensive safety analysis of the design structure was conducted to determine the minimum required adsorption force. A detailed evaluation of the electromagnet selection and performance reveals the impact of current on the magnetic adsorption force. Simulation experiments were performed to validate the optimal design parameters. The experimental results demonstrate that the proposed design is both rational and reliable, providing a solid foundation for future applications such as the inspection and maintenance of marine platform jacket structures.

Keywords: ROV; electromagnetic adsorption; mechanical analysis; design simulation.

1. Introduction

In the immense ocean, there exist rich biological resources, mineral resources and energy sources. The development and contention for the ocean have become key strategies for many developed countries [1-2]. Nevertheless, the mode of manual operation underwater is gradually unable to meet the requirements of complex underwater tasks in terms of cost, safety and efficiency. As a kind of high-tech equipment that can move in water, possess certain perception capabilities and assist or replace humans in completing various tasks, ROVs have significant application value in the fields of marine development and assisting underwater, etc.

ROV must be able to withstand the still water loads they are subjected to during deep sea operations [3]. Wall-climbing robot, as a special ROV, combines ground moving technology and wall adsorption technology to carry related equipment instead of humans to complete a variety of high-intensity, high-danger and repetitive tasks on steep walls, which can effectively improve work efficiency and ensure operation safety. At present, the Robot Innovation Center in Bremen, Germany, has developed a wheeled magnetic adsorption inspection Robot that can provide a real-time 3D attitude [4], and Li Jie [5] has developed a spherical tank wall climbing robot to realize the recognition and tracking of welds.

In this paper, a wall-climbing inspection ROV is designed to meet the needs of underwater magnetic wall detection. In order to realize wall detection, the key is to ensure the reliable wall-attachment of the ROV.

2. ROV Structure Design

2.1. ROV Design Requirements

This design adopts wheeled wall climbing structure, electromagnet adsorption and combined with the actual use of working conditions, the basic data of the ROV design is shown Table 1 below.

Table 1. Basic parameters of ROV

Self-weight	25kg
Self-weight	25kg
Overall dimensions	450*400*300mm
Load capacity	≤5kg
Maximum moving speed	4m/min
Working environment	Magnetic conductive wall

2.2. ROV Body Design

Figure 1 below shows the three-dimensional model of the wheeled electromagnetic adsorption wall-climbing ROV designed in this paper.

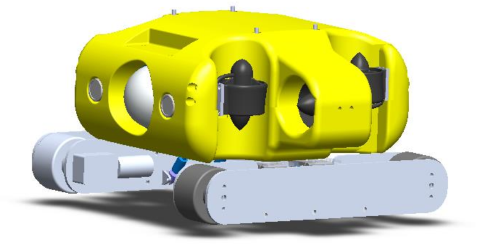

Fig. 1 ROV model diagram

Among them, the uppermost part is the detection module of the ROV, featuring high-brightness underwater lighting lamps, and the application platform can be equipped with replaceable cameras and sensors and other devices. The driving part is driven by differential motors located beneath the chassis of the wall-climbing ROV to drive rubber wheels. The walking part is actuated by differential motors that drive rubber wheels, and functions such as walking and steering are controlled through the different speeds and rotation directions of the wheels.

The underwater motion mechanism consists of thrusters. The ROV body is equipped with a total of 6 thrusters, among which there are 4 vertical thrusters and 2 horizontal thrusters. The vertical thrusters are installed at the four corners of the ROV body and are capable of achieving movements in three degrees of freedom in the vertical plane: floating and diving, flipping, and pitching.

The walking mechanism of the ROV adopts a variable-diameter walking mode. It can not only adapt to walking on a flat surface but also walk on magnetic walls of different diameters, to deal with various working conditions and enhance the efficiency of ROV application.

The adsorption part, as depicted in Figure 2, is composed of liftable electromagnets distributed between the wheels. Not being located beneath the abdominal wall significantly improves the obstacle-crossing ability. Strong magnetic force electromagnets are selected, which can not only facilitate demagnetization but also possess higher adsorption capacity than permanent magnets, thereby enhancing the safety of the equipment. The electromagnets are fixed on the crossbar between the wheels by bolts. When encountering obstacles, they can be naturally lifted, and when there are no obstacles, they can naturally fall. The bolts can adjust the height of the electromagnets, which can maintain a gap with the plane to reduce frictional resistance and will not affect the adsorption safety due to excessive distance.

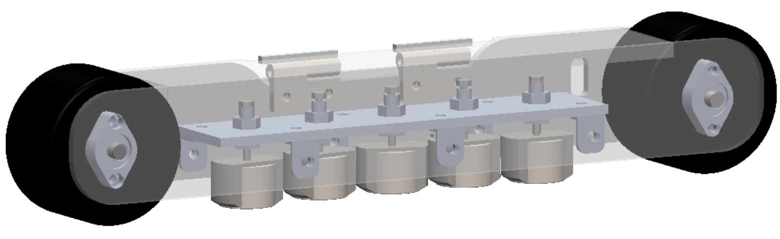

Fig. 2 Adsorption structure model diagram

3. Analysis of Mechanical Characteristics of ROV

This ROV has two operation schemes: swimming beneath the water surface and wall-climbing above and below the water surface. When the wall-climbing ROV operates below the horizontal plane of the marine platform's jacket, affected by its own buoyancy, the minimum magnetic adsorption force required for stable adsorption on the wall is obtained above the horizontal plane. Since this ROV adopts an electromagnetic adsorption solution, the magnetic adsorption crawler module of the robot needs to provide an appropriate magnetic adsorption force during the wall-climbing process, that is, the provided magnetic adsorption force should ensure that the ROV can stably adhere to the metal wall while not generating significant torque resistance for the underwater motor.

This paper establishes mechanical models for these two critical states [6-7], and explores the relationship between the magnetic adsorption force and the wall inclination angle and posture angle in these states, thereby determining the minimum magnetic adsorption force that the electromagnetic adsorption unit needs to possess.

3.1. Establishment of Spatial Pose

Let O-XYZ be the spatial coordinate system. Assume that the angle between any steel wall surface and the vertical wall surface is θ, and the coordinate system of the steel wall surface is o-xyz. The coordinate system of the ROV is o'-x'y'z', which is equivalent to the rotation of the wall surface coordinate system by an angle of β around the z-axis. G denotes the total gravitational force of the wall-climbing robot itself and its load. The ROV needs to overcome its own gravity. By decomposing the gravity into two directions parallel and perpendicular to the wall surface, G_x and G_y are obtained. The decomposition of G in the coordinate systems o-xyz and o'-x'y'z' can respectively be presented as:

$$\begin{cases} G_y = G\cos\alpha \\ G_z = G\sin\alpha \end{cases} \tag{1}$$

$$\begin{cases} G_{x'} = G\cos\alpha\sin\beta \\ G_{y'} = G\cos\alpha\cos\beta \\ G_{z'} = G_z = G\sin\alpha \end{cases} \tag{2}$$

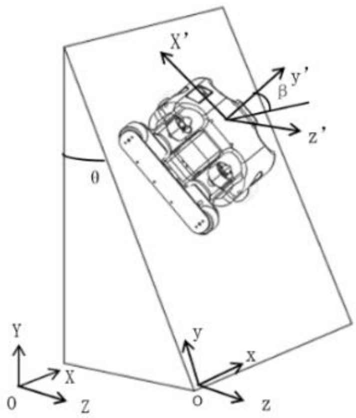

Fig. 3 Attitude diagram of ROV at any position

3.2. Static Security Analysis

The wall adhesion force analysis of the wall-climbing robot at rest is shown in Figure 4. Gravity G causes it to slide along the wall and overturn vertically. To ensure the safety and reliability of adsorption, the following analyses are carried out

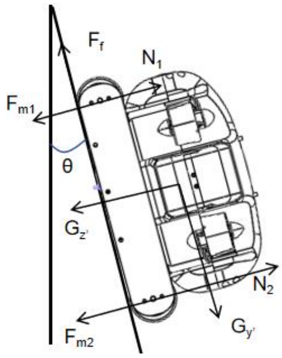

Fig. 4 Adsorption force analysis of ROV

3.2.1 Analysis of sliding along the wall

When the motor brake of the ROV is closed, if the frictional force is inadequate, the ROV is at risk of sliding downward under the influence of gravity. Hence, to guarantee that the ROV doesn't slide downward, the following requirements must be fulfilled:

$$\begin{cases} 4N = 2F_m + G_{z'} \\ F_f = 4\mu N \\ F_f > G_{y'} \end{cases} \tag{3}$$

Wherein:
F_f ——The friction force acting on the robot,
m ——Friction coefficient between rubber and steel plate,
N ——The support force of each wheel,
F_m ——The attractive force generated by each side's magnets.

The aforementioned equation analyzes the minimum condition for the ROV not to slip. Based on the force analysis, the following equation is derived:

$$F_m = \frac{G\cos\theta\cos\beta}{2\mu} - \frac{G\sin\theta}{2} \tag{4}$$

3.2.2 Analysis of overturning vertically

The ROV is in contact with the wall through its wheels. At this point, the overturning moment M_G generated by gravity can only be borne by the anti-overturning moment $M_{y'}$ produced by the first wheel at the top [8].

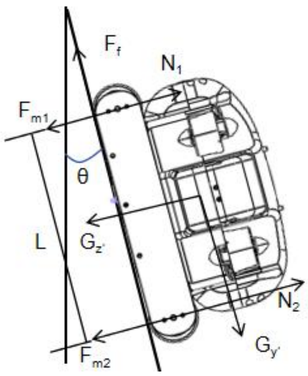

Fig. 5 Schematic Diagram of Overturning Criticality

Hence, to guarantee that the ROV doesn't undergo longitudinal inversion and overturning, the following requirements must be satisfied:

$$\begin{cases} M_{y'} = M_G \\ M_{y'} = 2\left(\dfrac{F_m}{2} - N\right)L \\ M_G = G_{y'} * H - G_{z'} * L/2 \end{cases} \quad (5)$$

In the equation, L denotes the distance along the wall surface from the uppermost wheel to the lowermost wheel of the track segment in contact with the wall; H represents the shortest distance between the position of the center of gravity of the ROV and the magnetic wall. By simultaneously combining formula, and with N > 0, if it's to satisfy the requirement that the ROV doesn't experience backward overturning instability, the minimum adsorption force is:

$$F_m = \frac{GH\cos\theta\cos\beta}{L} - \frac{G\sin\theta}{2} \quad (6)$$

3.2.3 Extreme value analysis of the ROV on jacket

According to the common instability states of the ROV described above, the minimum adsorption force required for the ROV is:

$$F_m \geq \max\{\frac{G\cos\theta}{2\mu} - \frac{G\sin\theta}{2}, \frac{GH\cos\theta\cos\beta}{L} - \frac{G\sin\theta}{2}\} \quad (7)$$

In the equation: K represents the safety coefficient, with K = 1.3; G = 250N, H = 150mm, L = 350m, and μ = 0.4. The curves of the allowable adsorption forces for anti-slip and anti-longitudinal overturning as functions of the wall inclination angle θ and the posture angle β are depicted in Figure 6. The curves therein illustrate the relationship between the allowable adsorption force F and the wall inclination angle θ and the posture angle β when G = 250N. When θ > 0, the allowable adsorption forces for anti-slip and anti-overturning decrease with the increase of θ; when θ = 0, the adsorption force can attain the maximum overall allowable force of 315N; when the posture angle β = 0, the allowable adsorption forces for anti-slip and anti-overturning also reach the maximum.

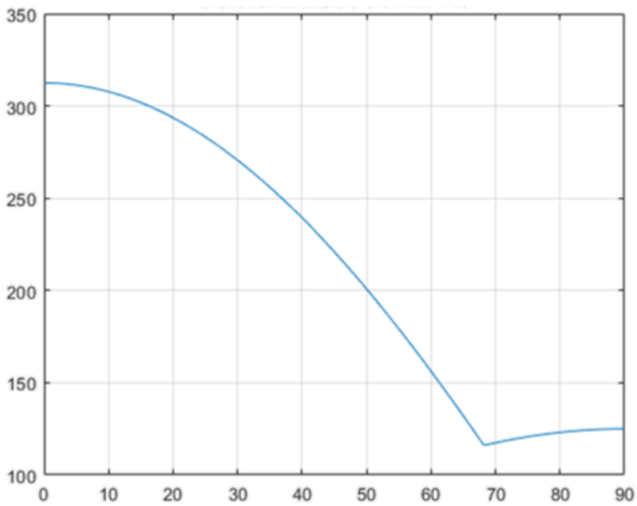

Fig. 6 The Variation Relationship of Allowable Adsorption Force with Wall Inclination Angle and Posture Angle

Therefore, when the robot can stably adsorb on the wall of the jacket structure and climb vertically, the adsorption force provided by each magnetic adsorption unit needs to satisfy:

F≥1.3*315 =410N.

4. Magnetic Force Analysis

4.1. Selection of Magnets and Their Arrangement Patterns

For wall-climbing robots, there exist three major adhesion approaches: vacuum adsorption, magnetic adsorption, and thrust adsorption. Among them, the vacuum suction cup type exhibits superior sealing but demands a higher degree of wall smoothness; thrust adsorption demonstrates strong adaptability to wall shape and material yet generates relatively high noise and possesses a larger volume; magnetic adsorption features lower energy consumption but it is challenging to separate the permanent magnet from the wall.

The three different adhesion modes of wall-climbing robots each have their own advantages and disadvantages. Therefore, the most suitable adhesion method should be selected based on the specific operational tasks required by the robot. Given the stringent requirements of vacuum adhesion for wall surfaces and the low efficiency of thrust adhesion, this design adopts the electromagnetic adsorption method. This choice is justified by the exceptional magnetic conductivity of the underwater platform material, as well as the controllability of the electromagnet, which permits effective demagnetization and retraction when power is turned off [9].

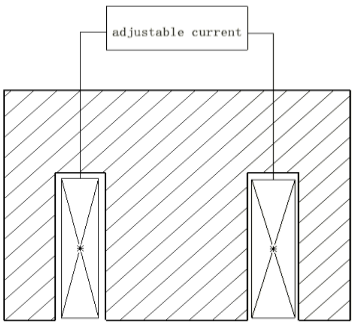

Fig. 7 Internal structure of electromagnet

Fig. 8 Electromagnet object

4.2. Parametric Analysis and Optimization Design of Electromagnetic Adsorption Unit

Electromagnet generates magnetic force by applying current or voltage to magnetize the armature. When the number of coils and the size of the magnet are fixed, the electromagnetic force is solely dependent on the magnitude of the current, ensuring that this force remains constant during the closing stroke [10]. The working principle involves energizing the coil, which generates magnetic field lines that pass sequentially through the armature and housing, forming a closed loop and creating north and south magnetic poles. When the coil is de-energized, magnetic field lines no longer traverse the closed loop, causing the electromagnetic force produced by the armature to dissipate.

Therefore, to determine the optimal current and air gap distance, magnetic force simulations of the electromagnet are conducted.

4.2.1 The influence of magnet parameters on adsorption characteristics

The electromagnetic iron was simulated using specialized software. A two-dimensional symmetrical model was developed based on the actual dimensions, as illustrated in the subsequent figure. The simulation reflects the real operating conditions, with the electromagnet designed to adhere to a 5 mm thick steel plate. The structure of the magnet includes a stainless steel metal shell and an internal brass coil, which has a thickness of 4.5 mm. The magnetic yoke is encased by the coil, allowing the magnet to be energized for magnetization and de-energized for demagnetization.

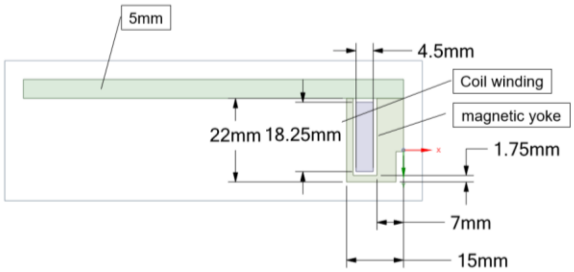

Fig. 9 Schematic diagram of electromagnetic simulation

Based on the electromagnetic iron simulation model established by Maxwell, the magnetic field boundary conditions are defined as balloon-shaped boundaries, while the coil excitation parameters, as well as the materials of the yoke, the adsorption wall, the number of coil turns, and the air gap distance between the adsorption wall and the magnet, are specified. The magnetic density distribution is illustrated in the subsequent figure. In selecting an electromagnetic iron, it is essential to consider not only the magnitude of the magnetic force but also the current and voltage compatibility with the robot's overall configuration. Additionally, the shape of the magnet should be optimized for practical applications.

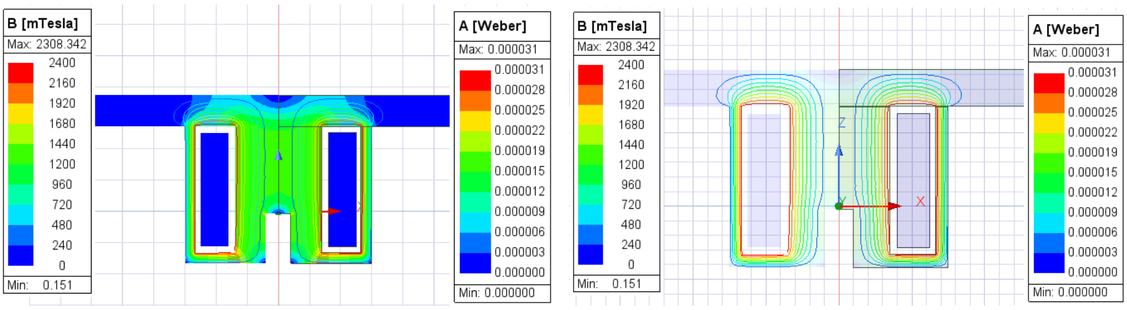

Fig. 10 Magnetic density nephogram

4.2.2 The influence of magnetic parameters on adsorption characteristics

The optimal current was determined using the control variable method by varying the current magnitude across different levels. Although a higher current produces a stronger magnetic force, excessive current can lead to magnetic saturation and compromise the overall safety and stability of the robot's operation. Conversely, an insufficient current may result in unstable adhesion. Consequently, the current variation was restricted to a range of 0 to 0.12 A. The calculation results are presented in the subsequent figure.

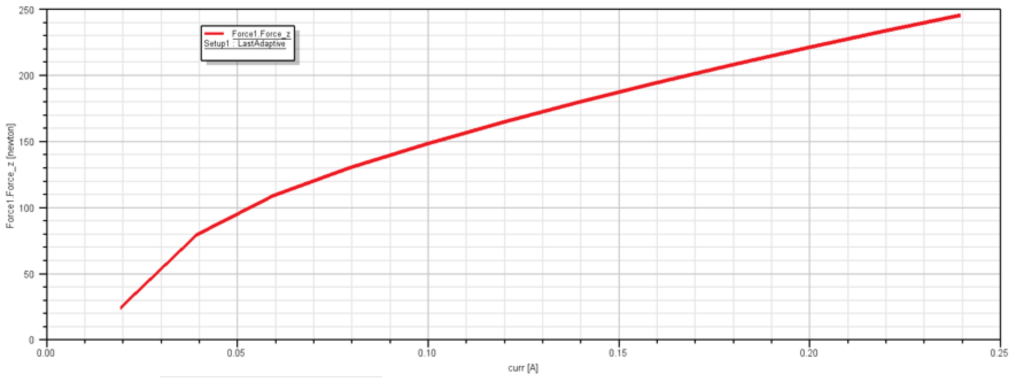

Fig. 11 The diagram of magnetic force varying with current

As illustrated in the preceding figure, the magnetic force exhibits a significant increase beyond 0.05 A. At 0.12 A, the magnetic force reaches its maximum stability, consistent with the overall operating voltage of the robot. This magnetic force satisfies the calculated requirements, ensuring safe and stable adhesion of the magnet. The fundamental electromagnetic data are presented in the table below.

Table 2. Basic Data of Electromagnets

Technical requirements	Design parameters
Rated Voltage	24V
Rated Current	0.12A
Number of Coils	2000
Thickness of Inner Magnet Shel	0.5mm

5. Experimental Design and Research

To validate the theoretical analysis, a magnetic force testing platform was constructed, and the adsorption force of the magnet was measured using a tensiometer. As illustrated in Figure 13, the magnetic adsorption unit was adhered to a vertical steel plate, with various current magnitudes applied to measure the magnetic force at different levels. Additionally, the height of the electromagnet was constrained to control the air gap distance. The magnetic force data at varying air gaps were recorded using a force gauge capable of capturing peak values and subsequently compared with the simulation results to assess the magnitude of any discrepancies.

Fig. 12 Magnetic Force Testing Platform

The simulation data before and after optimization, along with the experimental data obtained from tests, are presented as curves in Figure 14. The experimental data closely align with the simulation results, and both datasets exhibit similar variation trends, thereby confirming the reliability of the aforementioned optimization method. It is important to note that the experimental data are slightly lower than the simulation data due to inherent errors. This discrepancy arises because the data generated by simulation software are based on ideal conditions, whereas the actual adsorption force of the electromagnet tends to be somewhat lower than the theoretical value.

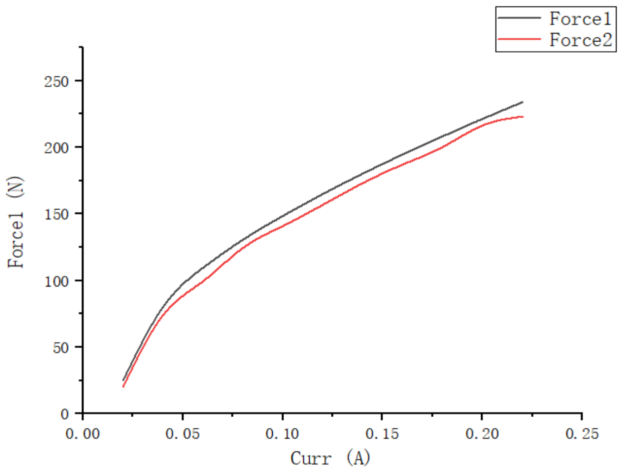

Fig. 13 Comparison diagram of simulation data and experimental data

6. Summary

In this paper, the magnetic adsorption ROV applied in the guiding operation of offshore platforms is taken as the research object. The static analysis is carried out on it, and the minimum magnetic adsorption force of 410N required for each side of the magnetic adsorption unit under different wall inclination angles and posture angles of the ROV is obtained.

The magnetic circuit structure of the magnetic adsorption unit is determined. The influence of different design parameters on the magnetic adsorption force of the magnetic adsorption unit is simulated by the Ansys Maxwell simulation software, and the optimal design scheme is obtained through multi-factor consideration.

The rationality and reliability of the adsorption structure design of the ROV are verified through experiments, providing a solution for the next research step of the wall surface maintenance work of offshore platform jacket structures.

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