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Motion Analysis of a Modular Inspection Robot with Magnetic Wheels*

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***Abstract* - A climbing inspection robot with four magnetic wheels is presented. Its structure is modular, which consists of a light manipulator module, an ultrasonic probes module and a weld testing sensors module. The robot not only can attract on the ferric and vertical wall, and but also can move to inspect the weld seam. It is driven by two DC servo motors. The motion of the robot on the vertical cylindrical vessel is analysed in detail. The position deviation and the angle deviation are adjusted and compensated with the geometric method. At last, the experiment of the motion on real vertical vessel is shown to verify the above analysis and design requirements of the inspection robot at Nanjing refinery factory in China.**

Index Terms* - *Climbing inspection robot, Magnetic wheel, Modular, Motion.

I. INTRODUCTION

A robot capable of moving on a vertical wall has been looked forward to for a long time [1]. The mobile robot with ultrasonic scanning is a useful device that can be applied to nuclear power plants [2] to protecting nuclear workers in highly contaminated areas or hostile environments, reduce human exposure not only to radiation, but also to hot, humid and oxygen-deficient atmospheres. In nuclear power plants, the reactor pressure vessels are one of the most important pieces of equipment in view of its function and safety. The vessels are constructed by welding large rolled plates, forged sections or nozzle pipes together. In order to assure the integrity of the vessel, these welds should be periodically inspected using sensors [3]. Such inspections have been performed using a conventional inspection machine with the manual method. In order to automate and cut human power, some systems are designed. Kim [3,4] developed an underwater mobile robot with magnetic wheels for the ultrasonic examination of the reactor vessel weld. By the aid of floats, the weight of the robot became zero in water. So the motion analysis in water was simpler than that in air. Sogi [5] developed an inspection robot to detect the weld seam for spherical storage tanks with the time of flight diffraction mode. Other climbing robots, such as the miniature robot-Crawler [6], the wall-climbing robot [7], and the SURFY[8], used vacuum suction cups to adhere to the wall.

We have developed a mobile robot with four magnetic wheels to detect the weld seam for the vertical cylindrical vessel with the tandem scan mode. The robot must be able of climbing walls and be of small size and light. It utilizes ultrasonic tandem way to automatically inspect the flaw of the weld seam.

II. STRUCTURE OF A CLIMBING ROBOT

The reactor pressure vessel has a cylindrical shape. It has many welds such as a circumferential seam, a weld of nozzles to the upper shell, a weld of flange to the upper shell and so on. When inspecting the welds of a vessel wall, the robot is moved to the outer wall of a reactor pressure vessel.

The robot consists of a light manipulator module, an ultrasonic probes module attached to its end effector and a weld testing sensors module. The robot has three degrees of freedom which are translation, rotation and probes' consecutive translation.

The manipulator module consists of the robot body plate, magnetic wheels, DC servo motors and so on. The reactor pressure vessel is composed of carbon steel and clothed with austenitic stainless steel. In order to climb the vertical wall of the vessel, the robot has four magnetic wheels.

Each magnetic wheel consists of two pieces of magnet and three pieces of pure steel plates. The ring shaped magnet has N and S poles on each side of the magnet. Its inner diameter is ϕ 50 mm and outer diameter is ϕ 91 mm. The circular pure steel plates are attached on each side of the magnet to maximize the attraction force to the vertical wall. Its inner diameter is ϕ 50 mm and outer diameter is ϕ 93 mm shown in Fig.1. It is about 2.5 Kg. Smooth rubber is clothed around the magnet to prevent slippage on the vertical wall. The robot with four magnetic wheels mounted on the parallel links with the robot body plate is about 20 Kg, as shown in Fig.2 and its technology specification illustrated in Tab.1. It makes the robot body parallel to the cylindrical wall. The four wheels are driven by two DC servo motors so that the robot has enough driven force when the robot swerves and one wheel is out of the wall. The robot can control the linear velocity and the angular velocity by the sum and difference of the velocities of the left and the right driving wheels.

The ultrasonic probes module consists of belt gears, probes and so on. It is used to scan the weld seam.

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The robot is induced by the weld test sensors module which has four optical fiber sensors 1,2,3,4 fixed in the left of the robot. The bottom of the sensors module has a spring to adapt to different cylindrical curvatures. At the beginning, the robot is put on the wall and the sensors module is parallel to the weld direction band. The robot walks along the direction tape and detects the deviation with the information of sensors, and moves in the appropriate direction to make this deviation zero.

In order to inspect the welds accurately, the robot should move exactly to the given position. However, controlling the robot's exact movements on the cylindrical wall is not a simple process. The robot's position and direction are determined by the sum and difference of the velocities of the left and the right wheel, which are driven by two DC servo motors. Because of gravity, the robot will slide on the vertical wall. Then the robot will deviate from its given position. So we must adjust the position and the pose of the robot.

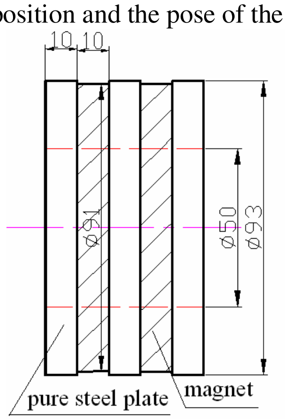
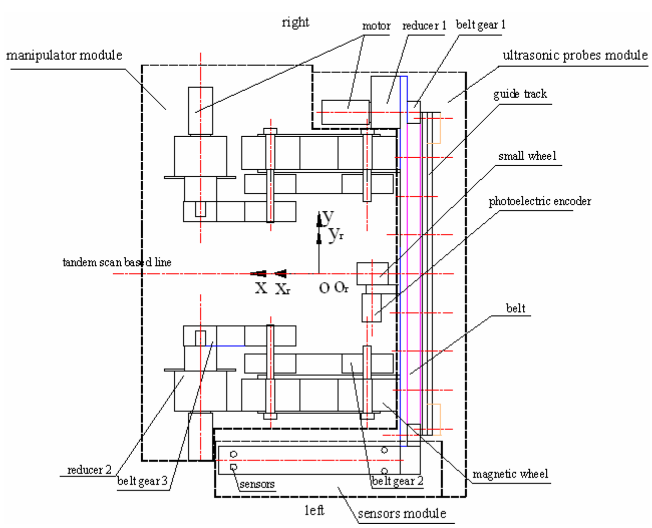
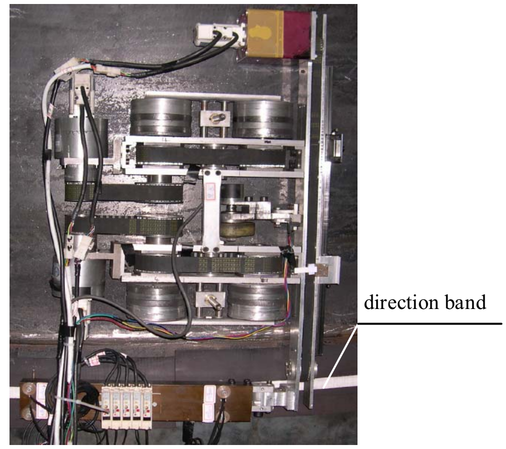


Fig.1 The structure of one magnetic wheel



(a)



(b)

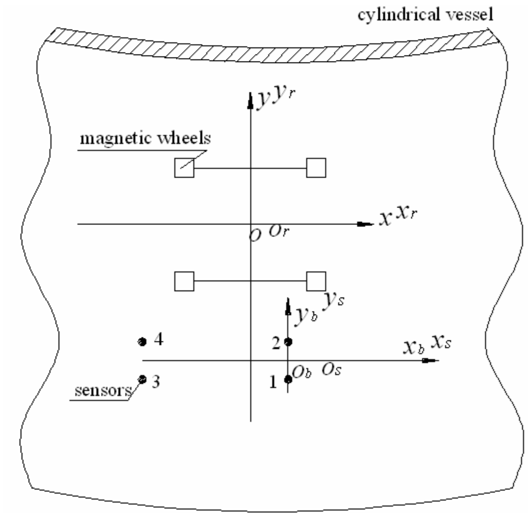
Fig.2 The structure of the mobile robot

Table.1 Specifications

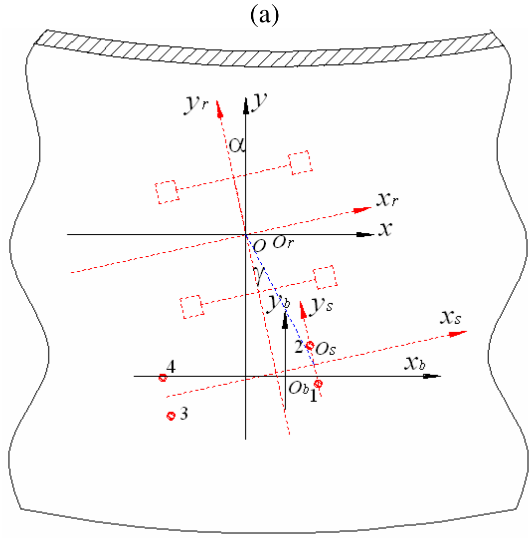
Outline Size	435mm(L)×730mm(W)×130mm(H)	
Weight	20kg	
Magnetic force	200kg (4 wheels in total)	
Movement Scope	x direction >=15m	
	y direction <=400mm	
Speed	x direction speed 95mm/s(0~70mm/s adjustable)	
	y direction speed 330mm/s(0~2000mm/s adjustable)	
Sensor	4 optic fiber sensors, precision 0.2mm	
	1 photoelectric encoder	

III. MOTION ANALYSIS

The coordinates of the robot, $o_r x_r y_r$ is illustrated in Fig.2, Fig.3. Point o_r is the symmetry center point of four wheels, the axis $o_r x_r$ is the symmetry center line of the left wheels and the right wheels. The axis $o_r y_r$ is parallel to the guide track of the tandem scan probes. In Fig.2, Fig.3, the axis ox fixed on the surface of the vessel is the tandem scan based line. o and o_r are the same point. In Fig.3, $o_s x_s y_s$ is the coordinates of the sensors module. The axis $o_s y_s$ is through sensor 1 and sensor 2. Point o_s is in the middle of sensor 1 and sensor 2. The axis $o_s x_s$ is parallel to sensor 1 and sensor 3. $o_b x_b y_b$ is the coordinates of the direction band. Before the motion of the robot, the coordinates $o_s x_s y_s$ and $o_b x_b y_b$ are at the same place. When the robot works, the coordinate systems $o_r x_r y_r$ and $o_s x_s y_s$ will change.



(a)



(b)

Fig.3 Motion analysis

In order to meet the need of the ultrasonic tandem scan, the robot must adjust its pose based on the sensors' status in time. In the Fig.3, four fiber sensors usually show the red color. When the robot deviates from the direction bend, the fiber sensors don't show the red color. The robot corrects its pose based on the status of four sensors. According to the deviation of the position and the angle, the status of sensors can be divided into 15 kinds, for example: ○●○●, ○●●○ etc. Here ○ means the dark of indicator, ● means light. The robot can reach the demand positions and angles by adjusting its motion. It includes the position deviation adjusting and the angle deviation adjusting.

A. Position Deviation Adjusting

The adjusting process of the position deviation has four steps. (a) The robot rotates an angle φ_1 about its center o. It arrives at the dotted line position displayed in the Fig.3 b. The solid line indicates the original position without deviation; (b) the robot moves forward x_1 in the direction $o_r x_r$; (c) the robot stops and rotates a converse angle φ_2 about its center; (d) the robot backs off the original position x_0 in the axis ox direction. Thus, the robot can fulfil the motion of y direction while the position of x direction is constant. Here the distance of $o_r o_s$ is l; the angle between the $o_r o_s$ axis and the y_r axis is γ; l, γ are the structure parameters of the robot; α is the rotation angle of the robot; the level distance from o_s to the y_b axis is Δx; the perpendicular distance from o_s to the x_b axis is Δy. We can obtain

1) The robot rotates the angle φ_1

$$\alpha = \varphi_1 \tag{1}$$

The level offset $\Delta x(\varphi_1)$ is

$$\Delta x(\varphi_1) = l\sin(\varphi_1+\gamma) - l\sin\gamma \tag{2}$$

The perpendicular offset $\Delta y(\varphi_1)$ is

$$\Delta y(\varphi_1) = l\cos\gamma - l\cos(\varphi_1+\gamma) \tag{3}$$

2) The robot moves forward x_1 in the direction $o_1 x_1$. The perpendicular offset $\Delta y(x_1)$ and the level offset $\Delta x(x_1)$ are

$$\Delta x(x_1) = x_1\cos\varphi_1 \tag{4}$$

$$\Delta y(x_1) = x_1\sin\varphi_1 \tag{5}$$

3) The robot rotates a converse angle φ_2

$$\alpha = \varphi_2 - \varphi_1 \tag{6}$$

The perpendicular offset $\Delta y(\varphi_2)$ and the level offset $\Delta x(\varphi_2)$ are

$$\Delta x(\varphi_2) = -[l\sin(\varphi_2+\gamma) - l\sin\gamma] \tag{7}$$

$$\Delta y(\varphi_2) = -[l\cos\gamma - l\cos(\varphi_2+\gamma)] \tag{8}$$

If $\varphi_2 = \varphi_1$, $\alpha = 0$, which means the angle adjusting is finished.

4) In order to compensate the offset in the axis ox direction, the robot must back off Δx_{1b}. The perpendicular offset $\Delta y_{x_{1b}}$ and the level offset Δx_{1b} are

$$\Delta x_{1b} = -\Delta x(x_1) = -x_1\cos\varphi_1 \tag{9}$$

$$\Delta y_{X_{1b}} = 0 \tag{10}$$

In conclude, the total level offset and the perpendicular offset are

$$\Delta x = \Delta x(\varphi_1) + \Delta x(x_x) + \Delta x(\varphi_2) + \Delta x_{1b} = 0 \tag{11}$$

$$\Delta y = \Delta y(\varphi_1) + \Delta y(x_1) + \Delta y(\varphi_2) + \Delta y_{X_{1b}} = x_1\sin\varphi_1 \tag{12}$$

B. Angle Deviation Adjusting

The adjusting process on the angle deviation is shown:

1) The robot rotates the angle φ_1. The position offset is shown in Eq.(2) and Eq.(3).

2) Compensating $\Delta y(\varphi_1)$ with the step (a) (b) (c) in section *A*, we can obtain

$$l\cos\gamma - l\cos(\varphi_1+\gamma) = x_2\sin\varphi_2 \tag{13}$$

In the process, the robot produces the level offset

$$\Delta x' = x_2\cos\varphi_2 \tag{14}$$

The total offset in the axis *ox* direction is

$$\Delta x_{total} = \Delta x(\varphi_1) + \Delta x' \tag{15}$$

3) Compensating Δx_{total}. The robot goes backward

$$x_{back} = -\Delta x_{total} \tag{16}$$

so

$$x_{back} = l\sin(\varphi_1 + \gamma) - l\sin\gamma + x_2\cos\varphi_2 \tag{17}$$

In practical adjusting process, influenced by the gravity and the friction, the deviation of the robot is different when the robot deviates to the left and the right. It must be compensated properly.

IV. EXPERIMENTS

We have the experiments in the real vessel at Nanjing refinery factory in China. The diameter of the cylindrical vessel is 3.4 meter and its thickness is 0.2 meter. The velocity of the inspection robot is 4mm / s. The motion distance is 1000mm. The adjusted time is 110s. The motion trajectory of the robot is shown in Fig.4. In the Fig.4, x represents the displacement in the level direction; y represents the deviation displacement; t_1, t_2 are the adjusted times, respectively. From Fig. 4, according to the above motion analysis, the pose of the robot can be adjusted. The robot moves along the tandem scan based line. The motion error is less than 1mm.

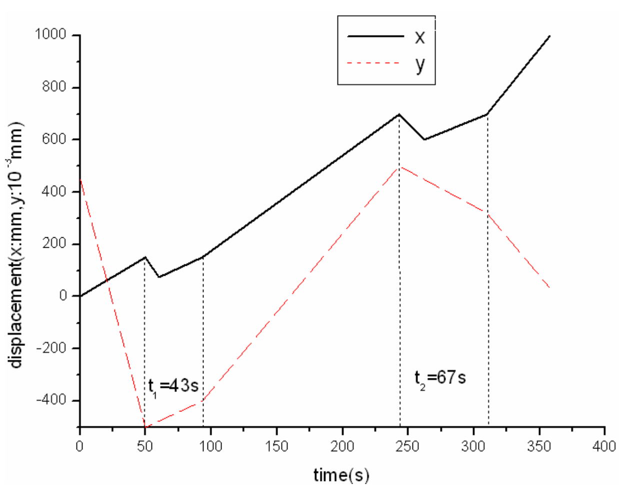


Fig. 4 The motion trajectory of the robot

V. CONCLUSION

A modular inspection robot with four magnetic wheels is presented. It consists of a light manipulator module, an ultrasonic probes module and a weld testing sensors module. It is driven by two DC servo motors. The robot not only can attract on the vertical wall but also can move on it. The motion of the robot on the vertical cylindrical vessel is analysed. The position deviation and the angle deviation are adjusted with the geometric method. At last, the experiment is shown to verify the above analysis in the real vessel at Nanjing refinery factory in China. The robot can move along the tandem scan based line. The motion error is less than 1mm.

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