A study on reducing power consumption of the centrifugal fan for the negative pressure adsorption wall climbing robot

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Abstract. In order to solve the problems of ship wall climbing robot’s great power consumption and high noises, a new approach to reducing power consumption and noises of the centrifugal fan was investigated. Firstly, the relationship between the air volume of a centrifugal fan and ship’s dip angle of the outer wall is obtained by analyzing force condition of the robot and the theory of negative pressure adsorption. Furthermore, by means of researching the process of fan’s speed-regulation through changing DC 0-3.3V of fan’s driver. We get the relationship between speed-regulation voltage after D/A convert of fan’s driver and ship’s dip angle of the outer wall. We proposed a control system that can automatically detect ship’s dip angle of the outer wall and adjust the output power of the centrifugal fan. Finally, the result of reducing power consumption and noises was tested effectively.

1. Introduction

As a special kind of robot, the wall climbing robot mainly works on places that are at a certain height from the ground such as vertical or steep surfaces of natural environments, artificial buildings and industrial facilities [1]. Nowadays climbing robot adsorption mainly includes vacuum adsorption, magnetic adsorption, biomimetic adsorption, vibration suction method and so on [2-5]. With the energy consumption and the rapid development of cleaning robot, many studies have been carried out to reducing power consumption of wall climbing robot include design high efficiency centrifugal fan and plan the movement rationally of robot with permanent magnet adsorption wheel [6-8]. The wall climbing robot adopts negative pressure adsorption and uses centrifugal fan as the negative pressure generator in this paper.

2. The theory of negative pressure adsorption

The adsorption system is composed of a centrifugal fan and sealing rubber around robot's chassis. The theory of negative pressure adsorption is that the centrifugal fan continuously discharges the gas in sealed cavity which is formed by robot’s chassis and outer wall of ship so a pressure difference is formed and the robot is adsorbed on outer wall of ship under this pressure difference. The adsorption system of the robot is shown in Figure 1.
3. The relationship between the dip angle and speed-regulation voltage

This section introduces the details of how to get the relationship between speed-regulation voltage of fan’s driver and ship’s dip angle of the outer wall by analyzing force condition of the robot.

3.1. When the robot in stationary state

Establish geodetic coordinate system O-XY and robotic coordinate system O₁-X₁Y₁. Analysis of force condition is shown in Figure 2 when the robot in stationary state.

According to static force analysis, the equations can be written as follows:

\[ N_1 + N_2 - F_1 - F_2 + mg \sin \alpha = 0 \]  \hspace{1cm} (1)

\[ f_1 + f_2 + mg \cos \alpha = 0 \] \hspace{1cm} (2)

Where \( F_1 \) and \( F_2 \) is the equivalent force acting on the robot’s two tracks and the robot’s chassis due to pressure difference respectively, \( N_1 \) and \( N_2 \) are the reactive force \( N_1 = F_1 \), \( N_2 = F_2 \), \( f_1 \) is the friction between the outer wall of the ship and the robot’s two tracks, \( f_2 \) is the friction between the outer wall of the ship and rubber around the robot’s chassis, \( f_1 = \mu_1 N_1 \), \( f_2 = \mu_2 N_2 \), \( \mu_1 \) and \( \mu_2 \) are the static friction factor.

Considering both of \( F_1 \) and \( F_2 \) are caused by the pressure difference between inside and outside of the robot’s cavity, the sum of \( F_1 \) and \( F_2 \) is equivalent to \( F \) that is adsorption force. In order to ensure the robot adsorbed on the outer wall of the ship safely, the adsorption force is calculated by:

\[ F_0 = mg \left( \sin \alpha + \frac{\cos \alpha}{\mu_1} \right) + N_2 \left( 1 - \frac{\mu_2}{\mu_1} \right) \] \hspace{1cm} (3)

Where \( F_0 \) is the minimum value of adsorption force that is critical adsorption force.
According to the Bernoulli’s principle, the relationship between fluid flow and pressure difference can be written as,

$$p_1 + \frac{1}{2} \rho v^2 + \rho gh = c$$  (4)

Where $c$ is a constant, $\rho$ is air density and $v$ is air velocity. Gravity can be ignored because of air and according to the Fluid’s Conservation of Energy

$$p_1 + \frac{1}{2} \rho v_1^2 = p_2 + \frac{1}{2} \rho v_2^2$$  (5)

If air velocity is zero in ideal windless conditions [9]. Referring to $v_1=0$, the pressure difference is expressed by following equation

$$p_1 + p_2 = \frac{1}{2} \rho v_2^2 \frac{F_0}{S}$$  (6)

Where $v_2$ is the air velocity in cavity of the robot, $p_1$ is atmospheric pressure, $p_2$ is the pressure in cavity of the robot, $S$ is the area of the robot’s chassis and $p_0$ is the pressure difference inside and outside of the robot’s cavity when $F=F_0$.

The air volume of centrifugal fan can be computed as [10]

$$Q = Ld v_2$$  (7)

Where $L$ is the perimeter of the robot’s chassis and $d$ is the gap between robot’s chassis and outer wall of the ship.

By solving Equation (3) and Equation (6), $p_0$ can further be given by

$$p_0 = \frac{1}{2} \rho v_2^2 = \frac{mg}{S} \left( \sin \alpha + \frac{\cos \alpha}{\mu_1} \right) + \frac{N_2}{S} \left( 1 - \frac{\mu_2}{\mu_1} \right)$$  (8)

By solving Equation (7) and Equation (8), the air volume of the centrifugal fan is calculated as follow:

$$Q^2 = \frac{2L^2 d^2 mg}{k^2 S p} \left( \sin \alpha + \frac{\cos \alpha}{\mu_1} \right) + \frac{2L^2 d^2 N_2}{k^2 S p} \left( 1 - \frac{\mu_2}{\mu_1} \right)$$  (9)

The air volume of centrifugal fan is proportional to fan’s rotary speed [11] so we assume $Q=kN$, where $k$ is a constant and only determined by fan’s structure. Fan’s rotary speed can be adjusted by changing DC 0-3.3V of fan’s driver so we assume that $U=jN$, where $j$ is a constant and only determined by the maximum speed of a centrifugal fan and the range of speed-regulation voltage. Referring to Equation (9), the relationship between ship’s dip angle of the outer wall and speed-regulation voltage of fan’s driver can be described by:

$$U^2 = \frac{2L^2 d^2 mg}{k^2 S p} \left( \sin \alpha + \frac{\cos \alpha}{\mu_1} \right) + \frac{2L^2 d^2 N_2}{k^2 S p} \left( 1 - \frac{\mu_2}{\mu_1} \right)$$  (10)

Because the sealing body of robot’s chassis is made of foamed rubber and PTFE so we can assume that $N_2$ is a constant. Referring to Equation (10), we can get that the speed-regulation voltage $U$ is only determined by the dip angle $\alpha$. It comes to a conclusion that we can change the DC 0-3.3V of fan’s driver by detecting ship’s dip angle of the outer wall so we can control the fan’s rotary speed. For variable torque loads like centrifugal fans, the fan’s output power is three cubed to the rotary speed therefore the fan’s output power can be adjusted by adjusting the fan’s rotary speed [12]. Because the fan’s rotary speed can be matched by detecting ship’s dip angle of the outer wall in real time, the adsorption force can be adjusted to an appropriate level. In this way, the purpose of reducing power consumption and aerodynamic noises is achieved [13].

### 3.2. When the robot in moving state

It can be ignored for the reason that wheels’ Moment of Inertia is small when the robot goes straight up in a straight line on the outer wall of a ship. Analysis of force condition is shown in Figure 3.

According to the D’Alembert’s principle, the equations can be written as follows:

$$N_1 + N_2 = F_1 + F_2 + mg \sin \alpha = 0$$  (11)

$$f_1 + f_2 = ma \cos \alpha = 0$$  (12)

$$(N_1 + N_2) L - (F_1 + F_2) L - ma H + mg L \sin \alpha - ma H \cos \alpha = 0$$  (13)
Where $a$ is the acceleration of the robot and the sum of $F_1$ and $F_2$ is equivalent to $F$. To ensure that the robot walks normally $f_1$ and $f_2$ must satisfy the following equation: $f_1 < \mu_1 N_1$, $f_2 < \mu_2 N_2$. By solving Equation (11), Equation (12) and Equation (13), the adsorption force can be computed as

$$F_0 = mg \left( \sin \alpha + \frac{\cos \alpha}{\mu_1} \right) + N_2 \left( 1 - \frac{\mu_2}{\mu_1} \right) + \frac{ma}{\mu_1}$$

(14)

The relationship between ship’s dip angle of the outer wall and speed-regulation voltage is expressed by following equation when the robot goes straight up in a straight line on the outer wall of a ship.

$$U^2 = \frac{2 \rho d^2 mg}{k^2 S_p} \left( \sin \alpha + \frac{\cos \alpha}{\mu_1} \right) + \frac{2 \rho d^2 N_2}{k^2 S_p} \left( N_2 - \frac{\mu_2 N_2}{\mu_1} + \frac{ma}{\mu_1} \right)$$

(15)

Figure 3. Dynamic force analysis.

4. The control system of the robot

In order to realize the lightweight design, the control system of the robot is composed of STM32 chips and it uses MPU6050 six-axis sensor as the orientation sensor. On the one hand, the controller can get the information of ship’s dip angle of the outer wall in real time through the MPU6050 and adjust speed-regulation voltage of fan’s driver through D/A convert. On the other hand, the controller obtains the information of obstacles in front of it through ultrasonic sensors and controls the servo motors for path planning. The function block diagram of the embedded control system is shown in Figure 4.

![Function block diagram of the embedded control system](image)

Figure 4. The function block diagram of the embedded control system.

5. Experiments

The model which is shown in Figure 5 is used for the experiments. The robot uses a centrifugal fan as negative pressure generator and two rubber tracks are used for walking. The steel plate is used to
simulate the outer wall of ship and the dip angle of it can be adjusted by the elastic nut during the experiment. Undeniably, the robot remains stationary throughout the process.

Figure 5. Photos of wall climbing robot.

The speed-regulation voltage of fan’s driver is DC 0-3.3V and the greater voltage leads the higher rotary speed and the greater output power. The fan’s driver is shown in Figure 6. The controller which is shown in Figure 7 can get the information of dip angle of the steel plate in real time and automatically adjust speed-regulation voltage of fan’s driver through D/A convert during experiments.

Figure 6. Control system of fan’s driver.  
Figure 7. The embedded control system.

In order to ensure good fan cooling conditions when the robot has sufficient adsorption force, rules speed-regulation voltage for 75% of the total voltage that is 2.5V. The static friction factor between the model and the steel plate is 0.81. In this case, the adsorption force is the largest when the dip angle is 39° [14]. Experiments show that the robot is adsorbed normally and does not slip when the speed-regulation voltage is 2.5V. The output power of fan was tested by a power meter and the noises level is measured at a distance of 30cm from the outlet directly opposite the outlet by a sound level meter.

The first experiment process is as follows: To ensure that the robot can be adsorbed in any angle of dip, the adsorption force must always be kept at the maximum one, which is the previous control idea. When the dip angle of steel plate changes from 0 to 60° the speed regulation voltage is always 2.5V during the experiment. We record the output power and the noises of centrifugal fan every 5s.

The second experiment process is as follows: When the dip angle of steel plate changes from 0 to 60°, MPU6050 detects changes of the dip angle and adjust speed-regulation voltage through Equation (10) in real time. In this way, the output power of centrifugal fan can be adjusted rather than a fixed value. The contrast diagram of instantaneous power and noises about two experiments is shown in Figure 8 and Figure 9 respectively.
Figure 8. Instantaneous power comparison about two experiments.

Figure 9. Sound level comparison about two experiments.

The dynamic loss, volume loss and wheel resistance loss caused by the actual gas viscosity are ignored during the experiments. The area enclosed by $t-p$ curve and coordinate axis is the power consumption in this period. Referring to Figure 8, there is a conclusion that the power consumed when the speed-regulation voltage follows the angle change is 42% less than the consumption when the voltage is constant. Meanwhile, noises also decrease significantly just as shown in Figure 9.

6. Discussions

Previously it has been reported that negative pressure goes through two processes that is the formation process and the maintenance process [11]. During the experiment, we found that once the negative pressure of robot’s cavity was formed the actual speed-regulation voltage is lower than the theoretical value when the dip angle changed, which is worth paying attention to.
7. Conclusions
This paper deduces the relationship between speed-regulation voltage of fan’s driver and the dip angle of ship’s outer wall when the robot is stationary or goes straight up in a straight line on the wall. To sum up, we proposed a control system that can automatically detect the dip angle of ship’s outer wall and dynamically adjust the output power of the centrifugal fan. In this way, the power consumption and noises of centrifugal fan can be reduced sharply compared with the previous control mode. Finally, this method proved is feasible by experiments. The theoretical and experimental result of research on reducing power consumption of the negative pressure adsorption robot contributes to further perfecting the performance of robot.

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