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A Small-sized Wall-climbing Robot for Anti-terror Scout

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***Abstract* – This paper presents a small-sized wall climbing robot for anti-terror and rescue scout tasks, which takes advantage of a method called critical suction. In this paper the critical suction mechanism is discussed in theory. Furthermore, the fluid model of the robot's suction system is set up using the fluid network theory. According to the dynamic response equation of the negative pressure inner the suction cup, the robot suction process on the wall is simulated. Finally, the results of the experiments for adsorbing on the sorts of walls proved this type of robot can be adsorbed on the surfaces.**

Index Terms - wall climbing robot, mobile robot, critical suction, fluid network.

I. Introduction

To wall climbing robots, they are usually used for extreme and dangerous environment, for instance: Buildings wall cleaning [1] [2] [3], Water-cooling tube cleaning for power station boiler [4] and Oil tank's volume measuring [5],etc. In the modern world, with the terrorism is very serious to countries, so developing an effective and practical robot for city high-rising buildings scout is significant.

Suction system is a key part for this kind of robot, because in the application field of the wall climbing robots, suction system is needed to provide enough suction force for the robot stability and reliability. Now, there are serial suction methods as follows: Vacuum suction or Negative suction [2] [3], Magnetic suction [4] [5], Thrust force [6] and Bionic suction [7]. If the suction force is too strong, the robot isn't able to move smoothly on the wall, and if it is too weak, it isn't able to stay on the wall at all. Therefore, we propose the "*Critical Suction*" theory. It synthetically makes use of the theory of negative suction and thrust, and then makes robot achieve homeostasis state in its suction cup, ensuring the robot to stay on the wall dynamically and move smoothly dynamically in the same time.

This paper proposes the Critical Suction Method (CSM), the method means that: the suction force includes two types of forces, one is the negative suction force generated inner suction disc, and the other is the thrust force generated by the propeller. And while the robot is adsorbing on the wall surface, the two forces could push it on the wall safely, and improve its obstacle-overleaping abilities.

In this paper, we use fluid network theory to set up a dynamic model and found the dynamic response equation of the negative pressure, and then simulate the transition process in order to see the responsive time of the pressure in the suction cup. The effect that the key parameters of the suction cup have on the suction characteristic will be analysed in the following. Finally, in the experiment section, the results for adsorbing on various kinds of wall surfaces are discussed.

II. Robot Suction Principle

Aim at the serious situations for anti-terror in the modern society, we presents a small-sized wall climbing robot using this novel adsorption method (CSM), Fig.1 is to express the robot concept equipped with a camera manipulator.

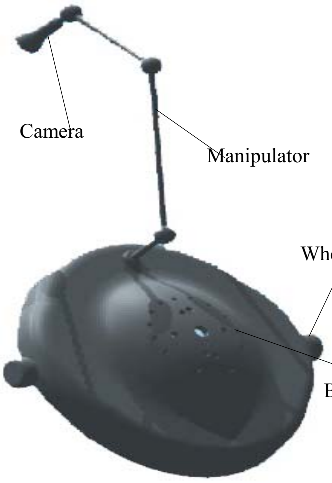


Fig. 1 This concept wall-climbing robot for scout task

The Fig.2 is the robot suction principle , It is mainly composed of suction cup, flexible sealed ring and propeller.

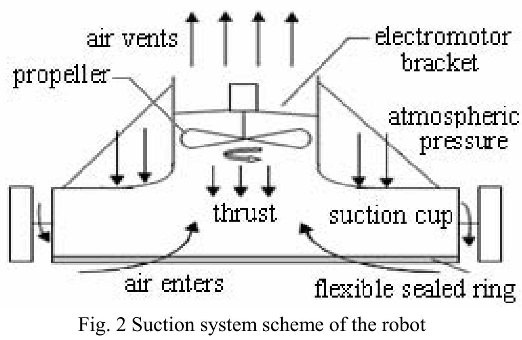


Fig. 2 Suction system scheme of the robot

Once propeller goes round and round at full speed, the air vents and thrust force produces that pushes the suction cup to the wall. What's more, air enters into the suction cup through the flexible sealed ring and it makes the cup achieve the negative pressure state. So there is the pressure force for the robot to suck on the wall. By adjusting the gap between the sealed ring and the wall surface, the critical suction would be obtained in the robot suction system. It also meets the demand that the robot can stay on the wall and move smoothly. And then we analyse the robot mechanics to find the critical point that makes the robot cup achieve a kind of dynamic suction balance state, and in this situation the suction force is consistent with the force that is need to make robot moving smartly, refer to reference [8] for the mechanics analysis.

III. FLUID MODEL OF THE ROBOT

When the robot moves on the wall, the airflow inner the suction cup is in a kind of dynamic status. As long as the negative pressure comes into being between outside and inside of the suction cup, the thrust creates, and then the robot is pushed on the wall by the atmospheric pressure and the thrust. In the next, we mainly discuss the cause of the negative pressure in detail. The definite air gap leakage is needed, so the air gap leakage in the air-sealed ring of the cup is an important key parameter.

A. Air fluid analyses

Supposing the conditions as follows [1]:

(a) There is no rotating airflow at the air-sealed surface between the sealed ring and the wall surface.

(b) The airflow leakage consists with radial direction along the wall surface.

(c) The Mach number *Ma*<0.3, namely. See Fig.3.

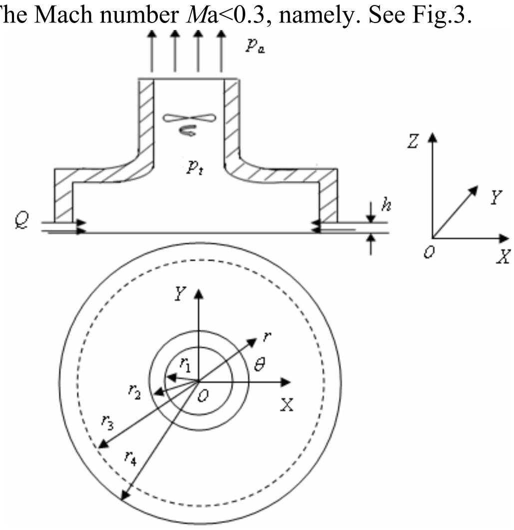


Fig. 3 Fluid model of the robot

In the suction cup, we set up cylindrical coordinates (r, θ, z). $v_\theta = v_z = 0$, and gas continuity equation:

$$\frac{v_r}{r} + \frac{\partial v_r}{\partial r} = 0 \tag{1}$$

The parameters have no relation with θ, therefore, according to Navier-Stokes equation [9]:

$$-\frac{1}{\rho}\frac{\partial P}{\partial r} + \frac{\mu}{\rho}\frac{\partial^2 v_r}{\partial z^2} = -\frac{v_r^2}{r} \tag{2}$$

$$\partial P / \partial \theta = 0$$
$$\partial P / \partial z = -\rho g \tag{3}$$

Where,

ρ - Gas density (kg/m^3).

μ - Aerodynamic adhesion coefficient (Pa.s).

Give the boundary condition: $z = 0$, $v_r \approx 0$; $z = h$, $v_r = U$, U is the airflow velocity where is in the max gap. So it can be given:

$$v_r = \frac{1}{2\mu}\frac{dP}{dr} z(z-h) + z\frac{U}{h} \tag{4}$$

Equation (4) is composed of two parts: one is because of the different pressure; another is because of the shearing flow.

B. Analyses of the sealed performance

Flexible material is used in the sealed ring of the robot. When the steady pressure is achieved, the airflow leakage *Q* in the sealed ring is equal to the air runoff that is vented when the propeller goes round and round. Hence, *Q* is a key parameter that can be used to estimate the performance of the cup sealed ring.

From (3) and boundary condition $r = r_4$, $P = p_a$; $r = r_3$, $P = p_t$ it is given:

$$p_t = p_a + \frac{6\mu U(r_3 - r_4)}{h^2} - \frac{6\mu Q \ln\left(r_3 / r_4 \right)}{\pi h^3} \tag{5}$$

$$Q = \frac{\pi h^3 \left(p_a - p_t + 6\mu U (r_3 - r_4) / h^2 \right)}{6\mu \ln\left(r_3 / r_4 \right)} \tag{6}$$

When the robot holds still on the wall, $U = 0$. Then

$$Q = \frac{\pi h^3 (p_t - p_a)}{6\mu \ln \frac{r_4}{r_3}} = \frac{\pi h^3 \Delta p}{6\mu \ln \frac{r_4}{r_3}} \tag{7}$$

Where,

Q - Airflow leakage (m^3/s).

p_a - Standard atmosphere (Pa).

p_t - Negative pressure inside the cup (Pa).

h - The gap between the sealed ring and the wall surface (m).

r_3, r_4 - Circumference's inside radius and outside radius of the sealed ring (m).

Because of $p_t < p_a$ and $r_4 > r_3$, $Q < 0$. It accords with the real airflow direction that enters into the cup from outside. According to the formula (11) and $\Delta r = r_4 - r_3$, the relation is simulated, see Fig. 4.

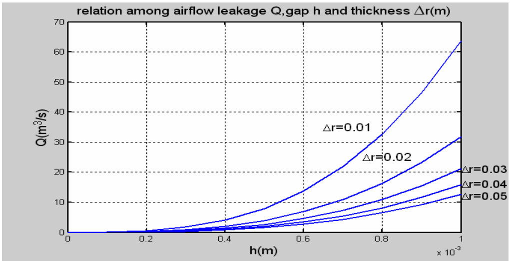


Fig. 4 Relation among airflow, the gap and the thickness of the sealed ring

From Fig.4, Q increases with the gap *h*, but it reduces when Δr , the thickness of the sealed ring increases. This supplies reference for the robot structure.

C. Fluid analyses inside the suction cup

When the airflow is steady in the suction cup, take on the control system, it is between the section ① and ②, see Fig. 5. v_1， p_1， A_1 and v_2， p_2， A_2 are respectively its airflow velocity, pressure and area of section, and Q_M is mass airflow.

From Bernoulli equation:

$$z_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = z_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + \frac{\zeta {v_2}^2}{2g}$$

z_1， z_2 - height dispersion of two sections relative to datum plane, here $z_1 = z_2$ (m).

ζ - Pipeline part drag coefficient.

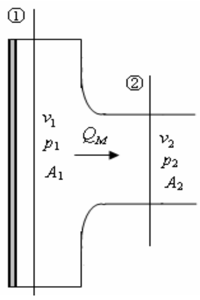


Fig. 5 Fluid analyses inside the suction

To section① and ② , the continuity equation is:

$$v_1 A_1 = v_2 A_2$$

According to fluid network theory [10], there is much damp because of the different section area and the part air loss in the air passage:

$$R_1 = \frac{Q_M}{2\rho A_1^2}, R_2 = \frac{Q_M}{2\rho A_2^2}, R_\zeta = \frac{\zeta Q_M}{2\rho A_2^2} \text{ then}$$

$$p_1 - p_2 = Q_M (R_2 - R_1 + R_\zeta)$$

$$R_{12} = R_2 - R_1 + R_\zeta$$

R_{12} - Equivalent damp between section ① and ②(1/m.s).

Unless pipeline length $l >> d$ （pipeline diameter）, because the damp in this case can't be calculated using the method in the pipe case directly, so we can use this method above to calculate approximatively. Actually, the smooth curve and the frustum methods are used at the joint. Then the former gets $\zeta \approx 0.05$, the latter gets $\zeta \approx 0.1$ [9], so $\zeta = 0.2$ is possible.

$$R_{12} = \frac{(1+\zeta) Q_M}{2\rho A_2^2} - \frac{Q_M}{2\rho A_1^2}, A_1 > A_2$$

The part $\frac{(1+\zeta) Q_M}{2\rho A_2^2}$ is important to the value of R_{12}. If the passage section area A_2 gets large, the value of R_{12} will reduce.

IV. FLUID NETWORK MODEL AND SIMULATION

A. Fluid network model

When the steady pressure is achieved, the airflow could be thought of as laminar flow. But when the fanner turns on or off and the robot meets the hole until the flow is steady, the period should be analysed using the fluid network theory. In the process, if the gas density and gas capacitance change, the airflow is thought of as compressed flow. Gas flow, pressure and glutinosity force in fluid mechanics are regarded as electric current, voltage and resistance in the fluid network. In addition, compressibility and airflow inertia are regarded as capacitance and inductance. Here it is defined that R_0 is the resistance between sealed ring and the wall surface. The fluid model is composed of two gas cavities in different radius. At the joints, gas flow is continuous, $Q_{I2} = Q_{II1}$, see Fig.6.

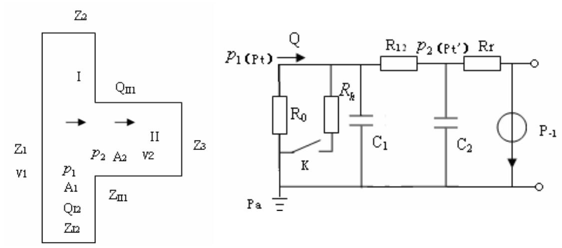


Fig. 6 Fluid network model

When the system is steady, the airflow doesn't change with the time. During the time, capacitance doesn't exist, namely, it is open circuit in the place of C_1 and C_2. Propeller is equivalent to electrical source that provides a constant voltage P_{-1} and inner resistance is described as R_r.

R_{12} is the equivalent resistance between the two negative cavities. The gas process is in constant temperature. The capacitances are given as follows:

$$C = \frac{V}{R_g T}, \quad Z = \frac{1}{jwC}$$

R_g - Gas constant ($\mathrm{m^2/s^2 \cdot {}^\circ K}$).

T - Absolute temperature ($T = 293^\circ \mathrm{K}$).

Inductance can be ignored because the gas changes on a low frequency. R_h is equivalent resistance of the slot on the wall.

B. Steady fluid network analyses in the suction cup

Fig.6 gives the equivalent electrical circuit of the fluid network system model. It has two capacitances. When there is no resistance R_h in the circuit, the total resistance can be given as follows:

$$Z = \frac{1}{jwC_2 + 1/R'} + \mathrm{R_r}\,,\; R' = \frac{1}{jwC_1 + 1/R_0} + R_{12}$$

When the pressure is at the state of dynamic equilibrium, it is a DC circuit. Then

$$p_1 = \frac{p_{\text{-}1}R_0}{R_0 + R_{12} + R_r}\;,\; p_2 = \frac{p_{\text{-}1}\left(R_0 + R_{12}\right)}{R_0 + R_{12} + R_r}$$

If there is a slot on the wall surface, there is a branch circuit of R_h. When the system works steadily, the formula $\frac{R_0 R_h}{R_0 + R_h}$ can replace R_0, so there is another parameter R_h to work on the system.

C. Negative response characteristic once the robot begins to contact with the wall surface

Once the suction cup begins to contact with the wall and turn on the fanner, the equivalent circuit is given in Fig. 7.

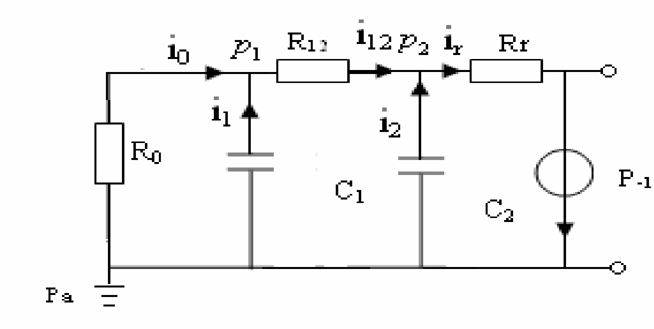


Fig. 7 Equivalent circuit of the system

$$\begin{cases} i_0 + i_1 = i_{12} \\ i_{12} + i_2 = i_r \\ i_1 = C_1 \dfrac{dp_1}{dt} \\ i_2 = C_2 \dfrac{dp_2}{dt} \end{cases} \quad \text{and} \quad \begin{cases} i_r R_r + p_2 = p_{-1} \\ p_1 + i_{12}R_{12} = p_2 \\ i_0 R_0 = p_1 \end{cases}$$

So

$$\begin{cases} \dfrac{dp_1}{dt} = -\left(\dfrac{1}{R_0 C_1} + \dfrac{1}{R_{12} C_1}\right) p_1 + \dfrac{p_2}{R_{12} C_1} \\ \dfrac{dp_2}{dt} = \dfrac{p_1}{R_{12} C_2} - \left(\dfrac{1}{R_{12} C_2} + \dfrac{1}{R_r C_2}\right) p_2 + \dfrac{p_{-1}}{R_r C_2} \end{cases}$$

$p_1(0) = 0$, $p_2(0) = 0$ are initialization conditions. We define a, b, c and d as follows.

$$a = -\left(\frac{1}{R_0 C_1} + \frac{1}{R_{12} C_1}\right), b = \frac{1}{R_{12} C_1}, c = \frac{1}{R_{12} C_2}, d = -\left(\frac{1}{R_{12} C_2} + \frac{1}{R_r C_2}\right)$$

The linear equations' discriminate is

$$\Delta = \left(a+d\right)^2 - 4\left(ad - bc\right) = \left(a-d\right)^2 + 4bc\,.$$

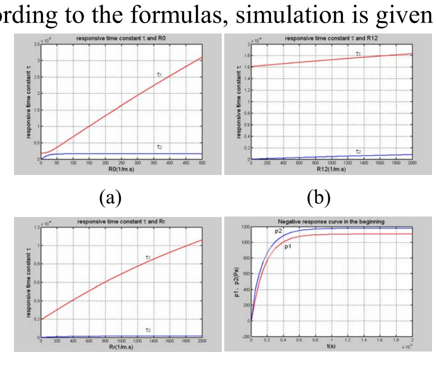
Because every parameter is positive, so $\Delta > 0$ and $\lambda_{1,2} = \dfrac{\left(a+d\right) \pm \sqrt{\left(a+d\right)^2 - 4\left(ad-bc\right)}}{2}$. The circuit response is over damping response and it is not an oscillatory circuit. Then

$$\begin{cases} p_1(t) = A_1 e^{\lambda_1 t} + B_1 e^{\lambda_2 t} + \dfrac{p_{-1}R_0}{R_0 + R_{12} + R_r} \\ p_2(t) = \dfrac{c}{\lambda_1 - d} A_1 e^{\lambda_1 t} + \dfrac{c}{\lambda_2 - d} B_1 e^{\lambda_2 t} + \dfrac{p_{-1}\left(R_0 + R_{12}\right)}{R_0 + R_{12} + R_r} \end{cases}$$

And

$$\begin{cases} A_1 = \dfrac{\left(\lambda_1 - d\right)\left(\lambda_2 - d\right)}{c\left(\lambda_2 - \lambda_1\right)} \dfrac{p_{-1}}{R_0 + R_{12} + R_r}\left(\dfrac{cR_0}{\lambda_2 - d} - R_0 - R_{12}\right) \\ B_1 = \dfrac{\left(\lambda_1 - d\right)\left(\lambda_2 - d\right)}{c\left(\lambda_2 - \lambda_1\right)} \dfrac{p_{-1}}{R_0 + R_{12} + R_r}\left(R_0 + R_{12} - \dfrac{cR_0}{\lambda_1 - d}\right) \end{cases}$$

According to the formulas, simulation is given in Fig. 8.



(a) (b)

(c) (d)

Fig. 8 Relation between responsive time constant and resistances and negative responsive curve in the beginning

The conclusions are as follows:

1) Latent roots λ_1 and λ_2 are relative to responsive time constant. Roots $\lambda_{1,2} < 0$ and $\lambda_{1,2} = f\left(\frac{1}{C_1}, \frac{1}{C_2}\right)$, it is clear that roots is a function for capacitances C_1, C_2.

$$C = V/R_g T = AH/R_g T$$

A - Area of the negative cavity.

H - Height of the negative cavity.

If the volume (AH) of the suction cup reduces, the responsive time constant will reduce. But it should be ensured there is always enough negative pressure in the suction cup.

2) Fig.8 (a), (b) and (c) show the relation between responsive time τ and each resistance (R_0 , R_{12} and R_r). τ_1 and τ_2 are respectively relative to latent roots λ_1 and λ_2 . Resistances almost don't affect the responsive time constant τ_2 , but they affect τ_1 greatly. Although the responsive time constants increase with all three resistances, relatively the resistance R_0 affects the responsive time more than the other resistances.

$$R_0 = \frac{\Delta p}{Q_M} = \frac{\Delta p}{\rho Q} = \frac{6\mu}{\rho \pi h^3} \ln\left(\frac{r_4}{r_3}\right) \tag{8}$$

In formula (8), increasing the resistance R_0 , there are two methods: reduce the gap and increase the thickness of the sealed ring.

3）Fig. 8 (d) shows the curve of dynamic response. The negative pressure is a transition process when the robot begins to touch the wall surface and the fanner turns on.

V. EXPERIMENT AND DISCUSS

For proving the robot adsorption capability using CSM, we made a simple prototype robot suction disc, it is shown in Fig.9. The suction disc is made up of a large disc, an air channel and a propeller.

Fig.9 New prototype of the robot

Fig.10, Fig.11, Fig.12 and Fig.13 show that the robot is adsorbing on various wall surfaces.

Fig.10 Adsorbing on glass wall

Fig.11 Adsorbing on rugged brick wall

Fig.12 Adsorbing on smooth brick wall

Fig.13 Adsorbing on cement wall

The gap between the wall surface and the disc is 10mm, and it is changeable in the above experiments.

Firstly, to the prototype of the robot disc, the disc diameter is 400mm, the weight is 2kg, and the payload is about 2.7kg, therefore, if a manipulator with a camera is light in weight, it is no problem to the scout task. Generally, use aluminum material to make the manipulator and using a mini-camera, the total weight of the manipulator can be less than 2kg.

Secondly, because it is a prototype, the air channel is as smoothly as streamline, so the impedance of the air is stronger. Therefore, the payload did not get maximum value.

VI. CONCLUSION

This paper proposes a new concept wall-climbing robot, adopted Critical Suction Method (CSM). With all these analyses, obviously this method can promote the robot stability and reduce the responsive time in the fluid transition process.

In its experiments, the result is proved that the robot can adsorb on sorts of wall surfaces and is not respect with the wall surface situation.

It is shown in Fig.9 to Fig.13, the prototype of the robot is just simple and ugly a little, so for the further work, we plan to make an official and optimized robot, and equip with a scout camera on it.

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