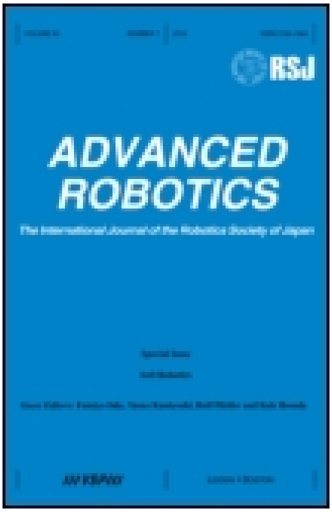

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Paper

Design of a robot capable of moving on a vertical wall

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Abstract—The development of a mobile robot which can work on the vertical walls of tall buildings, the side walls of large ships, etc. has been expected for a long time. A magnetic force or vacuum pressure is available to sustain the robot on a vertical wall, and wheels, crawlers and some other walking mechanisms can be used as the methods of moving. Many combinations of these mechanisms will be developed for various applications. Two kinds of robot model were built and tested. The air was sucked from the peripheral nozzle of the suction cup to the fan and crawlers were used as the moving system. There are two dangerous situations—slipping and falling, and their limits are determined. It is important to decrease the shock of an impulsive load, such as a falling body colliding with the robot on the wall. In such a case, a guard with a shock absorber is useful for avoiding this danger, and its optimum design condition is derived. The aerodynamic matching between the fan and suction cup is also important to understand the safety conditions and to design an active controller to avoid dangerous situations. It is investigated using the above models.

1. INTRODUCTION

The development of a mobile robot which can move on the vertical or overhanging walls of tall buildings, on the side walls of ships, etc. has been expected for a long time. The robot could then be utilized to carry rescue tools or to do some other work instead of man. In order to realize this robot, frictional force is required to sustain the robot or to move it upwards on the wall. A magnetic force or vacuum pressure can be used to produce the fixing force to the wall, and wheels or crawlers are available as parts of the moving mechanism on flat and wide vertical surfaces. A walking robot with suction cups is more attractive since it can move on a large irregular surface. Many combinations of these ideas can be developed for various applications in the near future.

In this paper a suction cup with a small vacuum pressure, less than 1000 mm H_2O negative, is considered. A small amount of air is sucked from the peripheral clearance of the cup, when it is moving on the wall, and it can move on the wall with small irregularities, when the brush and/or flexible skirt are employed to prevent air flow at the periphery of the cup.

Since 1965, we have built several kinds of mobile robot which can move on vertical walls and ceilings. Two examples are presented in this paper. In Fig. 1, Mod-1 is shown; it was a model to realize the idea of this mechanism and was constructed in 1966. Mod-2 is shown in Fig. 2; it was a more realistic model and was constructed in 1975. Each model had a suction cup, and the negative pressure in the cup was controlled by varying the rotational speed of the fan. The fan of Mod-1 was driven by a small AC-motor and that of Mod-2 by a small gasoline engine. Through the

Figure 1. Mod-1 built in 1966.

construction and experiments of these models, their performance could be understood clearly.

Each of the above-mentioned models has two dangerous situations, slipping and falling; the latter is fatal. By utilizing several cups connected to the fan independently these situations can be avoided. However, it is important to consider the safety conditions of a cup as the basic performance of this mechanism, which is represented in Section 2, before considering more complicated systems. In practical use, it is also important to consider the impulsive load, i.e. a collision with a falling body, for instance. In this case, a safety guard which has a shock absorber is effective and its optimum design technique is presented in Section 3.

On the other hand, as the amount of negative pressure in a cup depends closely on the fan performance, the aerodynamic matching conditions between them are derived for Mod-2 as an example. For the slow and sudden changes of the clearance, the path of the operating point is shown on the fan performance map and the dangers corresponding to these changes are discussed in Section 4. In Section 5, the overall safety conditions and the countermeasures for the dangers are summarized.

Figure 2. Mod-2 built in 1975.

2. SAFETY CONDITIONS

2.1. General conditions required to move a robot on a vertical wall

Rapid acceleration and deceleration of an automobile are easy on the ground, since a large frictional force is available. However, to move the robot on a vertical wall, the frictional force produced by the vacuum pressure in the cup must sustain not only the dead weight, but also the added weight produced by the upward acceleration. In general, the friction does not essentially depend on the contact area, so that there are no differences in frictional effect between tyres and crawlers. In practical use, however, there are some differences between them depending on the wall material or its surface conditions, as well known on the ground.

In order to move a suction cup on a vertical wall, a small clearance is required at the periphery of the cup, and a sufficiently low pressure must be kept in the cup with air flow through the clearance.

To move the robot on a ceiling or overhanging wall is easier than the movement on a vertical wall, therefore the latter is considered mainly in this paper.

2.2. The relation between fixing force and safety condition

The fixing force F perpendicular to the vertical wall is given by the product of vacuum pressure p and the suction cup area A as

$$F=pA. \tag{1}$$

The functional relations of area A and peripheral length L are given as

$$A=f_1(L) \quad \text{and} \quad L=f_2(A) \tag{2}$$

where f_1 and f_2 are functions depending on the shape of the cup. Now a single cup, shown in Fig. 3, is considered. The conditions required to avoid slipping and falling are given as the following relations, respectively;

$$F/W > 1/\mu \tag{3}$$

$$F/W > h/R \tag{4}$$

where W is the dead weight of the cup, μ is the friction coefficient, h is the distance from the centre of gravity to the wall surface, and R is the distance from the point where the force F acts on the support point S. To avoid falling, the robot should be designed under the following condition:

$$h/R < 1/\mu. \tag{5}$$

If the support point S is taken to be outside the cup and connected to the hinge P by a lever as shown in Fig. 4, the distance R becomes longer. Therefore this case is safer with regard to falling than the situation shown in Fig. 3.

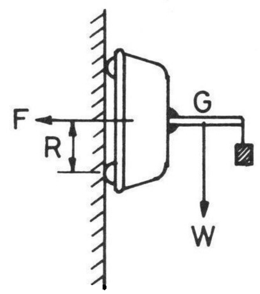

Figure 3. Schematic diagram of the moving robot on a vertical wall.

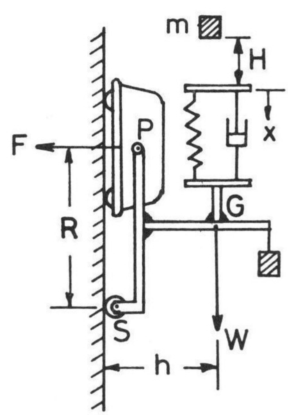

Figure 4. Schematic diagram of the moving robot with a damper.

The experiments were carried out with the cups shown in Figs 3 and 4 by using the rubber lips at the periphery of the cups instead of the wheels. The results are shown in Fig. 5. In the experiments wall materials of acrylic plate, aluminium plate and plaster board were utilized and each combination of rubber lip and these wall materials had a friction coefficient of $\mu=0.95$, 0.59 and 0.45, respectively. Falling was independent of the wall materials and equation (4) agreed well with the experiments.

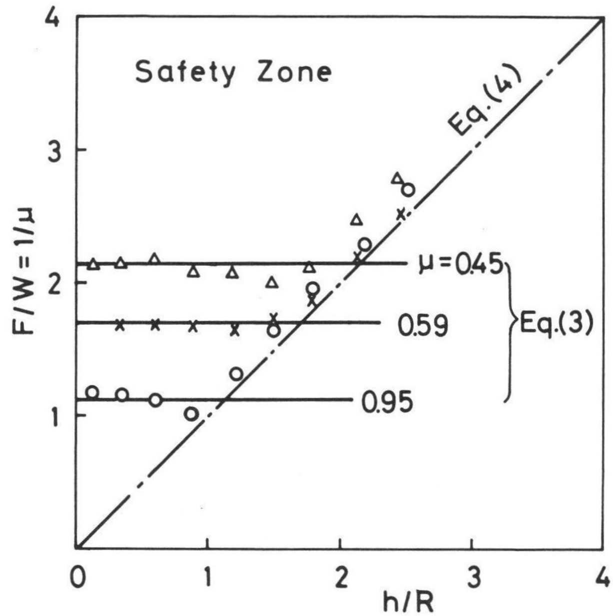

Figure 5. Safety range for falling and slipping.

3. DESIGN OF A DAMPER FOR IMPULSIVE LOAD

3.1. Impulsive load

It is necessary to be careful when an impulsive force acts on a robot in practical use. For example, there are impulsive forces such as the loading force of payload when the robot is utilized as a rescue machine, and the shock of colliding with a falling body when it is adopted as a fire robot, etc.

A safety guard with a damper is available for such impulsive loads. In Fig. 4 a damper composed of a spring and dashpot at the centre of gravity is shown schematically, and the case where a falling body of mass m falls from a height H and collides with the damper is considered. Then the impulsive force W_d can be given as

$$W_d = kx + c\dot{x} = m(g - \ddot{x}) \tag{6}$$

where x is the displacement of the damper, k is the spring constant, c is the damping coefficient and g is the acceleration of gravity. The initial conditions are

$$x=0 \quad \text{and} \quad \dot{x}|_{t=0} = \sqrt{2gH} \quad \text{for } t=0. \tag{7}$$

The following non-dimensional parameters are introduced by using the static load W_s ($=mg$) and the critical damping coefficient c_0:

non-dimensional impulsive load $\xi = |W_d/W_s|$

non-dimensional spring constant $\eta = \sqrt{2kH/W_s}$

non-dimensional damping coefficient $\zeta = c/c_0 = c/(2\sqrt{mk})$.

The solution of equation (6) is given with the angular velocity $\omega=\sqrt{k/m}$ as

(1) for $0<\zeta<1$

$$\xi=e^{-\zeta\omega t}\left\{\frac{\eta(2\zeta^2-1)-\zeta}{\sqrt{1-\zeta^2}}\sin\sqrt{1-\zeta^2}\,\omega t+(1-2\zeta\eta)\cos\sqrt{1-\zeta^2}\,\omega t\right\}+1 \tag{8}$$

(2) for $\zeta=1$

$$\xi=e^{-\omega t}\{1-2\eta+(\eta-1)\omega t\}+1 \tag{9}$$

(3) for $\zeta>1$

$$\xi=\frac{1}{2\sqrt{\zeta^2-1}}[\{\zeta+\eta-2\zeta^2\eta+(1-2\zeta\eta)\sqrt{\zeta^2-1}\}e^{-(\zeta+\sqrt{\zeta^2-1})\omega t}$$
$$-\{\zeta+\eta-2\zeta^2\eta-(1-2\zeta\eta)\sqrt{\zeta^2-1}\}e^{-(\zeta-\sqrt{\zeta^2-1})\omega t}]+1. \tag{10}$$

The solution ξ represents the damping vibration for $0<\zeta<1$, and the maximum value of ξ appears in the range of small ωt for each parameter of ζ. At this point, the maximum impulsive force acts on the robot, so that this force must be accepted safely by the damper. For example, $\eta=2$ is given, then the curves of ξ for a few ζ, such as $\zeta=0{\cdot}3$, $0{\cdot}5$, $1{\cdot}0$ and $1{\cdot}5$, are shown in Fig. 6 against ωt. In the case of $0<\zeta<1$, the time t_0 for the maximum value of ξ is given as

$$\omega t_0=\frac{1}{\sqrt{1-\zeta^2}}\tan^{-1}\frac{(4\zeta^2\eta-2\zeta-\eta)\sqrt{1-\zeta^2}}{4\zeta^2\eta-2\zeta-3\zeta\eta+1}. \tag{11}$$

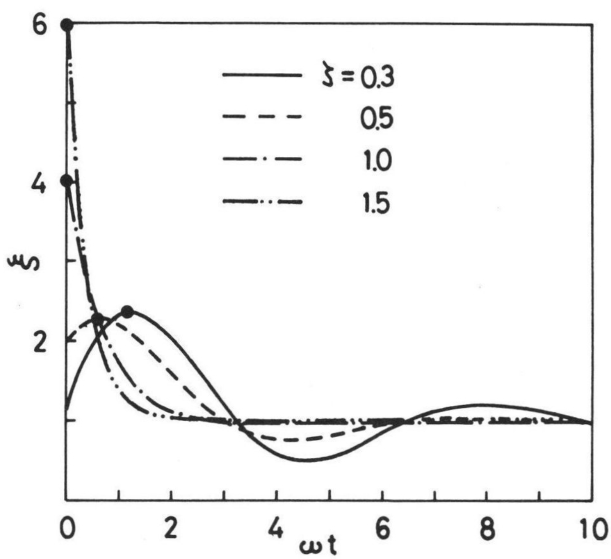

Figure 6. Time-dependent changes of impulsive force.

For $\zeta\geqslant1$, $t_0=0$ results. The maximum values of ξ vs. ζ are plotted in Fig. 7 with the parameter of η. There is a minimum value for each curve, and this point means the optimum combination of spring constant k and damping coefficient c for given conditions of m and H. ξ of this point is put as ξ_0 and it is shown in Fig. 8 vs. η. If η is given by another condition, ζ and ξ_0 are obtained from Fig. 8 and the required fixing forces to avoid slipping and falling are determined by the following relations, respectively:

$$F_d > W_d/\mu = (W_s/\mu)\xi_0 \tag{12}$$

$$F_d > \gamma W_d = \gamma W_s \xi_0 \tag{13}$$

where $(W_d + W)$ or $(W_s + W)$ are to be used instead of W_d or W_s, respectively, if the dead weight of the robot is taken into account, and $\gamma = h/R$.

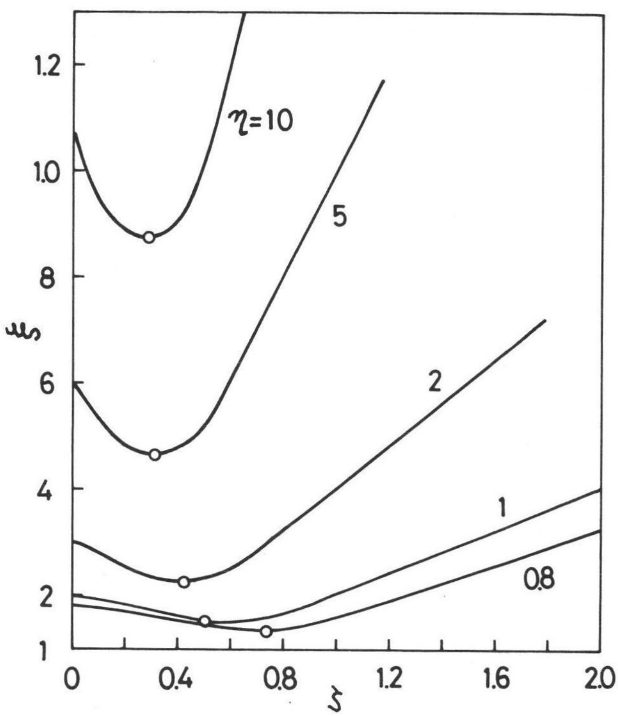

Figure 7. Relations between non-dimensional impulsive force and damping coefficient with the parameter of spring constant.

3.2. Damper design

The displacement of the damper can be obtained by solving equation (6). The displacement for the static load W_s is defined as x_0 $(= W_s/k)$, and the non-dimensional displacement $\lambda = x/x_0$ for a dynamic or impulsive load is given as:

$$\lambda = e^{-\zeta\omega t}\left\{\frac{\eta-\zeta}{\sqrt{1-\zeta^2}}\sin\sqrt{1-\zeta^2}\,\omega t - \cos\sqrt{1-\zeta^2}\,\omega t\right\} + 1. \tag{14}$$

The maximum displacement is obtained by putting $t = t_0$ in the above equation,

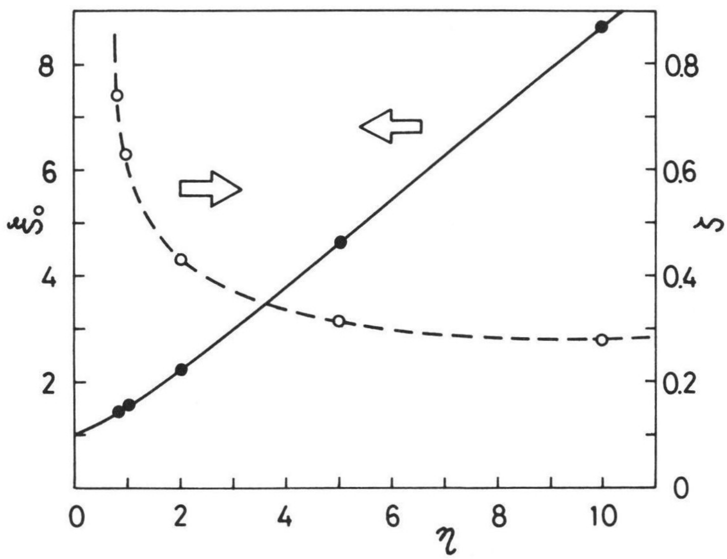

Figure 8. Minimum impulsive force vs. spring constant.

which is shown in Fig. 9 as λ_0. Therefore the optimum design point of a damper for a given mass m and height H of a falling body is summarized as follows:

(1) If the maximum allowable displacement λ_0 is given, the corresponding η is determined from Fig. 9, and the spring constant k is obtained.

(2) From Fig. 8, ζ and ξ_0 are determined for the above η, then c is given by ζ and the required minimum fixing force F_d can be obtained from equations (12) and (13).

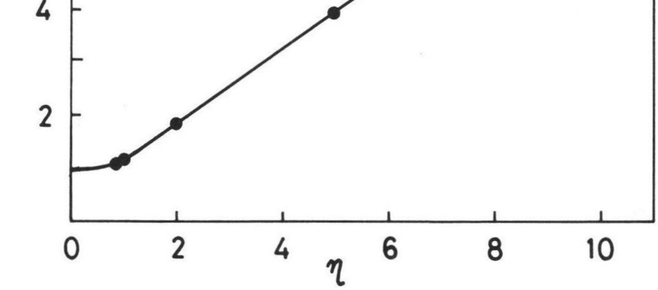

Figure 9. Impulsive displacement of the damper.

If an unrealistic value of F_d is obtained for a given λ_0, another λ_0 must be tried again and the iterative procedure is required to find a suitable combination of ξ_0 and F_d.

Although this design method can determine the optimum combination of k and c for a given impulsive load, it has to be noted that the optimum combination is not determined for an unexpected amount of impulsive load.

4. MATCHING OF THE FIXING FORCE AND FAN PERFORMANCE

The fixing force required to sustain the robot on a vertical wall is closely related to the fan performance, therefore the matching of these is a very important factor for discussing the safety condition and it is done by using Mod-2 as an example.

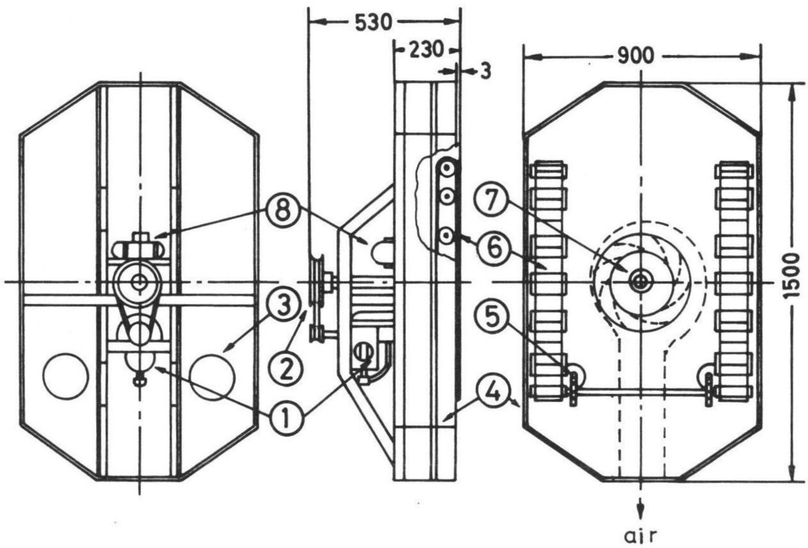

Figure 10. Drawing of Mod-2. ① Engine, ② Pulley, ③ Driving motor cover, ④ Brush and flexible skirt, ⑤ Driving motors, ⑥ Crawlers, ⑦ Fan, ⑧ Fuel tank.

4.1. Aerodynamic performance of Mod-2

A drawing of Mod-2 is shown in Fig. 10 and its specifications are presented in Table 1. As the centre of gravity of the model is $h/R = 0.44$, falling does not occur when $\mu = 1.0$, as already given by equation (5).

Table 1.
Specifications of the components of Mod-2

Engine	Two-cycle gasoline engine, cylinder volume 50 cm^3
Fan	Centrifugal type, outer diameter 400 mm
Driving motor	100 V, 500 W, AC motors
Moving device	Crawlers, length 820 mm, width 100 mm
Reduction gear	2-stage spur (1/20) and worm gears (1/50)
Area of suction cup	$A = 1.2$ m^2
Peripheral length of suction cup	$L = 4.2$ m, with brush and flexible skirt
Total weight	$W = 44$ kgf

The aerodynamic performance was measured as follows: A duct was connected to the fan inlet at the centre of the suction cup and the air flow was controlled by a valve inserted on the middle of the duct. The air mass flow was measured near the inlet of the duct, and the negative pressure corresponding to the pressure in the cup was measured at the fan inlet. These measurements were done under a constant revolutional speed of the fan.

In the next step, the model was fixed on the vertical wall and the clearance between the periphery of the suction cup and the wall surface was adjusted in three steps. In each step, the air mass flow and the negative pressure were measured by varying the fan revolutional speed.

The obtained fan performance (solid lines) and the matching lines for three clearances (dot-dashed lines) are shown in Fig. 11. The abscissa represents the air mass flow Q and the ordinate is the negative pressure p and the fixing force F. The fan performance is given with the parameter of rotational speed n, and the peripheral clearances are given by δ_e. The operating points under full engine throttle are represented by Z, Y and X for three clearances, respectively, and the curve connected to these points indicates the operating line of full engine throttle. If the minimum required negative pressure is measured when the model is fixed on the vertical surface, the friction coefficient of the crawler can be estimated. On a rough concrete surface, a minimum required negative pressure of $p = -35$ mm H_2O was obtained in the experiment. Therefore the fixing force was $F = 42$ kgf and as the dead weight of Mod-2 was $W_s = 44$ kgf, a friction coefficient of $\mu = 1.05$ was determined. In Fig. 11, the points U, V and W represents the minimum required negative pressure for each δ_e respectively, and the safety margins are given by the pressure differences between these points and the full engine throttle points, respectively. With regard to point U, the margin is only 15 mm H_2O; for point W, however, it is about three times the minimum pressure and it corresponds to a fixing force of $F = 130$ kgf. From these experimental results it can clearly be seen that the suction cup has two advantages by using a brush and/or flexible skirt at the periphery: one is the effect of sealing air leakage, so that a lower negative pressure is kept in the cup; and the other is the effect of easy movement on a rough surface. The smaller the amount of air leakage, the less power is required. As the limit of this characteristic, a vacuum cup can be utilized to carry the glass plate without any power to hold it up.

There is the brush and flexible skirt at the periphery of the model and as the most of the pressure loss of leaking air is produced when it passes through them, the negative pressure is nearly the same everywhere in the cup. The air is sucked by the pressure difference between atmospheric pressure and the negative pressure in the cup, and its velocity can be estimated by the Bernoulli equation under the assumption of no loss at the peripheral clearance. The equivalent nozzle area, i.e. the equivalent clearance δ_e, is assumed by dividing the air mass flow by the above velocity, which is used as the parameter in Fig. 11. The operating situation shown in Fig. 2 is given by X in Fig. 11.

4.2. Static performance

The friction coefficient between the wall surface and the wheels or crawlers determines the minimum negative pressure required. In the case of Mod-2, the friction coefficient μ is plotted on the right-hand side ordinate in Fig. 11 to show the relation of μ and p. For example, for $\mu = 0.5$, the minimum required negative pressure is $p = -75$ mm H_2O, and the model must slip when it operates at point X.

When the model is moving on an irregular surface, a change of clearance often

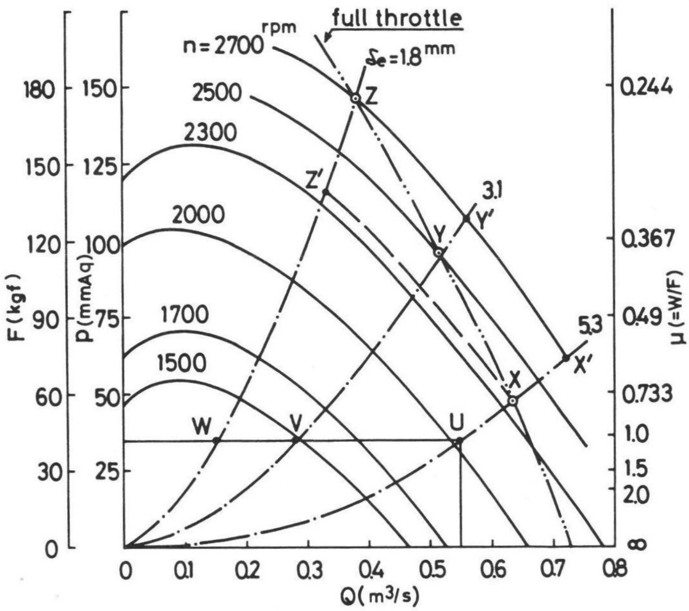

Figure 11. Aerodynamic performance of Mod-2.

occurs. If the change is not very sudden, the fan operating line is given by a steady-state curve almost parallel to X–Y–Z in Fig. 11.

4.3. Dynamic performance

An abrupt change of the clearance depending on the irregularity of the wall surface leads to a change of pressure and air mass flow. Then the rotational speed of the fan changes until a torque balance between the engine and the fan is achieved. The relation is given as

$$I\dot{\Omega}=\eta_m T_E - T_F \tag{15}$$

where I is the moment of inertia of the rotating parts, Ω is the angular velocity of the fan, η_m is the mechanical efficiency between the engine and fan, T_E is the driving torque and T_F is the required fan torque. In the steady state, $\eta_m T_E - T_F = 0$, so that Ω=constant. As T_F changes abruptly by changing the air mass flow, Ω varies until equation (15) is satisfied. From ref. 1 it is known that the transfer function is given by the first-order delay for a simple arrangement of the fan and duct system. In this case, nearly the same relation can be estimated, since the arrangement is not so complicated. For an assumed step increase of air mass flow by changing the clearance δ_e from 1.8 to 5.3 mm, the operating line is given by Z→X′→X. As there is the effect of the moment of inertia of the rotating parts, the operating point moves from Z to X′ instantaneously with a constant revolutional speed, and after that both the pressure and air mass flow decrease to the situation of X with decreasing revolutional speed. For a step decrease of the clearance, the operating point moves on the line of X→Z′→Z.

For a slow increase of the clearance, a smoother curve is obtained in the region of the above step change and steady-state curves. On the contrary, for a slow decrease, it is given in the region between the curves X–Z′–Z and Z–Y–Z for full engine throttle. Although there is an overshoot of mass flow at the point X′ for a rapid increase of the clearance, the negative pressure at the point is lower than that of point X, so that a dangerous situation does not occur on the curve Z–X′–X. In general, it can be seen from the steady-state curve that there are not many differences between rapid and slow changes.

5. OVERALL SAFETY CONDITIONS

A suction cup has the advantage that it can sustain a heavy load with small power on a vertical wall, when air leakage is small at the periphery of the cup. On the contrary, it has the drawback of difficulty in moving on a large irregular wall surface. The overall safety conditions at the design phase are summarized as follows:

(1) Falling is a fatal danger, so if possible, it should be avoided by a condition given in equation (5).

(2) The brush and flexible skirt are useful as a seal to prevent air leakage at the periphery of the cup.

(3) It is desirable that a few cups connected independently to the fan are used to avoid the fatal danger of falling.

(4) It is important to have a guard with a damper for expected or unexpected impulsive loads.

For operation, the following should be considered:

(5) The engine throttle must be controlled so that the negative pressure in the cup is kept sufficiently low by sensing itself. In this case, the smaller the moment of inertia of the rotating parts, the quicker the expected response.

(6) In an emergency, the peripheral seal must be controlled as fast as possible in order to reduce air leakage, and recover the lower negative pressure in the cup.

A walking mechanism with suction cups has a more flexible applicability for large irregular surfaces, and is currently being investigated.

6. CONCLUSIONS

A robot which can move on a wide and flat vertical wall is very attractive and has a wide applicability. Firstly, the safety conditions of a suction cup were tested as the basis of this type of machine. Secondly, the safety conditions for an impulsive load were considered and a design method of a damper which can decrease the impulsive force was represented. Thirdly, the aerodynamic matching between the fan and suction cup was analysed using Mod-2 as an example. From these studies the following conclusions can be made:

(1) There are two kinds of danger, i.e. slipping and falling, for a suction cup on a vertical wall, and the safety ranges are represented clearly.

(2) For an unexpected impulsive load such as collision with a falling body, a guard with a damper is effective in avoiding the danger; the required design condition of this has been derived.

(3) By using Mod-2 as a model, aerodynamic matching between the fan and suction cup has been discussed.

(4) The operating points for an abrupt change of air mass flow which occurs when the robot proceeds on an irregular surface, have been obtained and represented on the fan performance map.

(5) Under these analyses, the overall safety conditions have been summarized.

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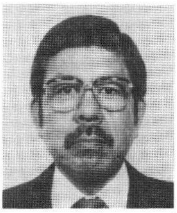

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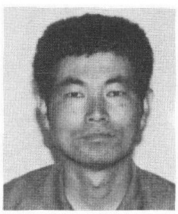

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