A Wall-Climbing Robot Using Propulsive Force of Propeller*

(Mechanism and Control System in a Strong Wind)

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In the previous report, the mechanism of a wall-inspection robot which is capable of moving in a weak wind on a vertical wall was investigated. For emergency use of a wall-climbing robot, such as in rescue, and fire-fighting, the robot must be able to move in strong and turbulent winds at any time. Therefore, the control system for large wind load is important. A combined control system consisting of a thrust force controller, a frictional force augmentor and a damper is used, and its performance is estimated by a computer simulation technique. The safety of the robot is ascertained for an actual turbulent and strong wind gust.

Key Words: Robot, Mechatronics and Robotics, Moving Robot, Motion Control, Control Device, Wall-Climbing Robot, Vertical Wall, Thrust Force, Propeller

1. Introduction

In the previous report⁽¹⁾, the mechanism and control system of a wall climbing robot capable of moving in a weak wind on a vertical wall were investigated.

For emergency use of a wall-climbing robot such as in rescue or fire-fighting, the robot must be able to move in strong winds at any time⁽²⁾. In general, the wind speed cannot be predicted in advance, and the controller has a certain amount of time lag; hence there is a danger of the robot slipping from the wall due to a sudden change in wind load. In order to prevent this, it is necessary to use a supporting force without time lag to counteract the change of wind speed. For this purpose, a wing or wing-shaped robot body is attractive, because it can produce lift force toward the wall and can be used to increase the frictional force between wheels and wall surface. It is called a frictional force augmentor in this paper. For

the low-frequency component of the wind gust, the thrust force controller is effective in compensating the wind load by controlling its magnitude and angles. On the contrary, the linear damper is effective in decreasing the vibration produced by the high frequency component of turbulent wind load. Therefore the effects of the combined control exerted by a thrust force controller, a frictional force augmentor and a damper are examined by a computer simulation technique. Firstly, the responses for the step and ramp inputs are obtained. Secondly the frequency responses are examined. Thirdly, the responses for the actual turbulent wind are tested, and the safety of the robot is ascertained⁽³⁾⁻⁽⁶⁾.

2. Control Conditions

2.1 Concept of control system

As the characteristics of a wind gust on the wall of a high-rise building cannot be observed in advance, the control is started after the change in wind speed is sensed, and the time lag of the controller becomes a major problem.

The wind on the front surface of a building is almost a crosswind for the wall-climbing robot and it

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$$F_s = -\mu(T_z + L_A) - \sqrt{(T_y - W)^2 + (T_x - D)^2} \\ \doteq -\mu(T_z + L_A) - |T_x - D| \quad (3)$$

In this case $T_y - W = 0$ is required in an unsteady wind, so that F_s is given as Eq. (3), where L_A is the lift force of the wing, D is the total wind load, and T_x , T_y and T_z are the components of T in x , y and z directions, respectively.

To move the robot any place on the wall in a turbulent wind, the wheel-driving mechanism can be used. However, it leads to a weight increase, and therefore it is not always a better choice.

2.3 Characteristics of control components

2.3.1 Control of propulsive force

The propulsive force is regulated by control of engine revolutionary speed, and the time-dependent variations of thrust force components depend on the control mechanism. In the simulation study these are given by the values of the model presented in the previous report as follows⁽¹⁾.

(1) The aerodynamic load decreases the acceleration of the propeller when the revolutionary speed increases. On the contrary, when the revolutionary speed is decreasing it increases the deceleration. The time-dependent characteristic of thrust force is assumed as a first-order lag and the time constants of acceleration and deceleration are given as $\tau = 0.2$ s, and 0.15 s, respectively.

(2) The inclined angle of thrust force ϕ is controlled by a servomotor and the angular velocity is given as $\omega = 0.47$ rad/s (constant) with dead time of $\tau_d = 0.2$ s.

(3) To simplify the control system, the inclined angle θ is assumed as constant and it is set before moving the robot.

It is given as a parameter in the simulation.

2.3.2 Performance of wing-shaped body

The robot body is covered by a fairing to form a wing section and it can produce the lift force toward the wall by a crosswind, as stated above. The same effect can be produced by setting a wing on the robot.

To obtain the performance of the wing-shaped body near the wall surface, a model study was carried out in a wind tunnel. The lift and drag forces are given in general,

$$L_A = C_L(1/2)\rho U^2 S \quad (4)$$

$$D_A = C_D(1/2)\rho U^2 S \quad (5)$$

where C_L and C_D are the lift and drag coefficients, respectively. Here, ρ is the density of air, U the mean crosswind velocity, and S the projected area of the wing. C_L and C_D are obtained by the experiments and given in Fig. 4 as an example. By giving a small angle of attack, a large ratio of L_A/D_A can be obtained. It can be assumed that the wind turbulence is large on

the wall of building; thus a small amount of lift force, $L_A/D_A = 2$, is used in the calculation, that is,

$$-\mu L_A = D_b \quad (\mu = 0.5) \quad (6)$$

where D_b is the drag force of the robot body.

2.3.3 Characteristics of damper In general, the higher-frequency components of turbulent wind give a smaller wind force; however, when there is an abrupt change in wind speed, there is a chance of slipping at any time. Also the engine vibration is a cause of slipping. These forces can be decreased by the damper installed between the robot body and wheels. The characteristics of it are assumed to be natural frequency

$$\omega_n = \sqrt{k/M} = 1 \text{ Hz} \quad (7)$$

nondimensional damping coefficient

$$\zeta = C/(2\sqrt{kM}) = 1 \quad (8)$$

where k is the spring constant, and M the mass of the robot.

2.4 Combined characteristics of controller

Equation (6) shows that the wind load of body D_b can be compensated by the frictional force of wheels. Then if the wind load of propellers D_p can be supported by the thrust force component and the effect of the damper, the safety of the robot can be ensured. The wind load of the propeller depends on the inclined angle and wind velocity. Its magnitude is nearly the same as the wind load of the body for the wind speed of $U = 30$ m/s and the inclined angles of $-30^\circ < \phi < 30^\circ$. The thrust force controller is effective for low-frequency change of wind load; on the contrary, the damper is for high-frequency change. Therefore, there must be a middle range of frequency where the controller is not effective. To be safe in this

Fig. 4 Performance of wing-shaped body near the wall surface

range, the thrust force margin is necessary.

2.5 Range of thrust force

If the thrust force is large enough for a wind load, the safety of the robot can be ensured in a turbulent wind at any time. However, it must be difficult to obtain a sufficient margin of thrust force, since a larger payload is expected in some case, especially in an emergency. In the simulation it is assumed as 20%, that is, $T_{\max}=1.2W$. The safety of the robot is examined in this thrust force margin.

2.6 Effect of the wing in a constant-speed wind

A limit of thrust force is given as above; then the thrust force angles to upwind ϕ and toward the wall θ must be controlled to compensate the wind load. There is a relationship between ϕ and θ as follows,

$$\phi_{\max} = \cos^{-1} [1 / \{ (T_{\max}/W) \cos \theta \}] \quad (9)$$

The effect of the wing is calculated for the constant-speed wind, and the results are shown in Fig. 5. In Fig. 5(a), the result without lift force is shown, and the supporting force $F_s/W < 0$ can be seen for small wind speed. For the case taking the wing effect into consideration, shown in Fig. 5(b), the supporting force is positive for large wind speed. Therefore it can be seen that the lift force of the wing-shaped body can increase the effect of the thrust force controller.

3. Results of Dynamic Simulation

3.1 Transient responses for step and ramp changes of wind speed

It is dangerous to test the robot directly in a strong wind on a wall, so the simulation study is carried out before the testing.

As a turbulent wind involves abrupt changes of wind speed, the transient responses for the step change of wind speed are examined first. A few examples of results are shown in Fig. 6. The angle θ is fixed as $\theta=20^\circ$. As the controller has many nonlinear components, complicated results are obtained. For larger changes of wind velocity $U=10\sim 30$ m/s, the support-

Fig. 5 Effect of wing-shaped body for constant-speed wind

ing force $F_s/W < 0$ can be seen for step and sharp changes of ramp inputs. A response for the step change of $U=10\sim 20$ m/s is also shown in the same figure, and this curve shows that the minimum point on the supporting force is almost zero and this means the limit of wind speed change.

An analytical expression of a response for the step input is shown in Fig. 7. Curve ① shows the input, curve ② the thrust force angle ϕ , and curve ③ the magnitude of thrust force. The wind load of the body is given by curve ④, and curve ⑤ is the frictional force produced by the lift force, which has the same magnitude but opposite direction with the wind load of the body. Curve ⑥ shows the wind load of propeller, and curve ⑦ is T_x/W . Curve ⑧ is the F_s/W without the effect of damper, and curve ⑨ is the F_s/W

Fig. 6 Transient responses of supporting force for step and ramp inputs

Fig. 7 Analyzed response of supporting force for a step input

with damper, and it is the same curve shown in Fig. 6.

3.2 Frequency response of the controller

A few examples of frequency response of supporting force are given in Fig. 8 for $U=10\sim30$ m/s. The angle of thrust force directed to the wall side θ is constant ($\theta=20^\circ$). The frequency of input is changed in the range of $n=0.5\sim4$ Hz. For $n=0.5$ Hz, the change of supporting force is very small, since the thrust force controller can follow the input change very well. On the other hand, for $n=4$ Hz the damper can work well and the change of F_s/W is small. Then the intermediate range of these inputs must be difficult to control. The most dangerous situation is $n=1$ Hz in this figure; however, there is a possibility of increasing the supporting force by adjusting the angle θ . This is examined and the results are shown in Fig. 9. Here, $\theta=30^\circ$ has the largest margin. When $T_{\max}/W=1.2$ is assumed, the larger θ is selected, and ϕ must be smaller as given by Eq. (9). Therefore the limit of θ

Fig. 8 Frequency responses of supporting force

Fig. 9 Frequency responses for 1 Hz input

is $\theta=33.6^\circ$ and $\phi=0^\circ$ in this case; that is, the frictional force becomes larger for large θ . However, as ϕ is small in this case, it is difficult to compensate the wind load. As a compromise, $\theta=30^\circ$ is obtained.

The complicated curves in Fig. 9 are caused by the frictional force which is positive for wind speed increase and negative for decrease.

3.3 Responses of supporting force for an actual turbulent wind

A few examples of responses for an actual turbulent wind are given in Fig. 10. The wind velocity changes by about $U=8\sim40$ m/s, and large and abrupt changes are involved in the fluctuations. The supporting force curves are given by a parameter θ . Both curves of $\theta=20^\circ$ and 30° have positive supporting force margins throughout the whole range and the curve of the latter has a larger one at about $F_s/W=0.1$. Hence the combined controller can support the robot on a wall in the given turbulent wind.

The long-duration responses of supporting force are given in Fig. 11. In the figure the supporting force without the effects of lift force produced by the wing-shaped body and of the damper is given, and it has many negative supporting force ranges which indicate slipping on a wall.

3.4 Responses of supporting force on a rear wall surface

In the experiment, the turbulent wind is observed on the rear wall surface of a building, as mentioned above. A typical wind turbulence is assumed, that is, the wind direction changes quickly to the opposite direction with the mean velocity of $0.5U_\infty$. This is given by the sinusoidal curves of wind speed changes,

Fig. 10 Responses of supporting force for an actual crosswind

Fig. 11 Long-duration responses of supporting force

Fig. 12 Responses of supporting force on a rear wall surface

Fig. 13 FFT-analyzed wind components

and U_∞ is given as $U_\infty = 30$ m/s. The frequency of wind direction changes is given in the range of $n = 1 \sim 4$ Hz. It is also assumed that the same magnitude of lift force is produced by the wing-shaped body for winds of the opposite direction. The results are shown in Fig. 12. The thrust force control angle $\phi = 0^\circ$; then $\theta = 33.6^\circ$ is fixed, since the change in ϕ produces a larger

drag force on the propeller due to the time lag of the controller. The minimum positive supporting force $F_s/W = 0.05$ can be obtained for $n = 1$ Hz.

From the above simulation study, it can be seen that the combined controller can work well for a given arbitrary severe turbulent wind.

4. Statistical Characteristics of Turbulent Wind

An example of FFT-analyzed results of the given turbulent wind is shown in Fig. 13. In the range of small frequency, the amplitude of turbulent wind is larger and vice versa. As discussed above, the frequency around 1 Hz is important for the controller. This range is not especially large, so the control system can work well. In general, the relationship between the scale of robot and wind characteristic is important. For a large-scale model, the lower-frequency component of turbulent wind produces a larger wind load, and it has larger amplitude. Therefore, larger lift force of a wing-shaped body is expected in this case.

5. Conclusions

A wall-climbing robot which can be used in an emergency is required to have characteristics of both fast and safe movement on the wall of a high-rise building in a strong and turbulent wind. A wall-climbing robot having a propeller as a thruster was developed, and it has a long body and many wheels to move on an irregular wall surface at high speed. The control system for the wind load is very important. A combined controller consisting of three parts, a thrust force controller, a frictional force augmentor and a damper, was considered. The supporting force was examined for the assumed wind speed changes and an actual turbulent wind.

(1) For step and ramp input of wind speed change, the supporting force becomes negative; that is, slipping occurs for large wind speed changes.

(2) The frequency responses are examined. Around 1 Hz frequency of wind speed change is most severe for the controller.

(3) The responses for an actual turbulent wind are examined, and for some combinations of thrust force angles and its margin, a supporting force margin of about 10% can be obtained.

(4) The response of supporting force is also obtained for assumed turbulent wind on the rear wall surface, and $F_s/W > 0$ is ascertained.

(5) By these analyses it is shown clearly that the robot can move in a high-speed wind on the front surfaces and in a turbulent one on the rear wall surfaces of buildings.

In future work, another mechanism will have to

be developed to ensure a soft landing to prevent danger on the ground when the robot falls from the wall surface due to an unexpected strong wind.

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