A WALL CLIMBING ROBOT FOR INSPECTION USE

Akira Nishi
Faculty of Engineering
Miyazaki University
Miyazaki 889 - 21
JAPAN

SUMMARY

A wall climbing robot using propulsive force of propeller has been developed for wall inspection use. Thrust force is inclined to wall side to make use of frictional force between wheels and wall surface, and the robot can move on a vertical wall safely. A long body with many wheels is considered to move on an irregular wall surface. A strong and turbulent wind is predicted on a wall of high - rise buildings, so that, a frictional force augmentor is employed to avoid slipping of the robot. A controller characteristic is tested by computer simulation for an abrupt change of wind gust, and safety locomotion in high speed turbulent wind can be attained.

Keywords : Wall climbing robot, vertical wall, thrust force, propeller, locomotive robot, wheel locomotion

1. INTRODUCTION

A robot capable of moving on a vertical wall has been expected for a long time to use it for wall inspection, wall repair, carrying a small paylord when buildings are constructing, or for maintenance use. These hazardous tasks are suitable missions for the robot instead of man. Three quite different types of robot models have been developed for last 20 years in our laboratory. The first model has a large sucker and crawlers in it as a moving mechanism [1]. The second one, shown in Fig. 1, was a biped locomotive model and it has a small sucker on each foot [2]. This type can be applied to the various types of irregular surfaces which have convex or concave parts on the wall, such as eaves, window flames, etc., so it has a wider applicability. The walking motion, however, is not so quick that it takes much time to climb up the buildings. There are many purposes to use the wall climbing robot in convenience, and some of them require a quick motion of climbing up on a wall. The third model aims at these purposes, which is discussed in this paper [3]. It has a propeller to produce the thrust force, and it is inclined to the wall side to make use of the frictional force between wheels and wall surface. It is shown in Fig.2 and its mechanism is discussed and required force is calculated.

The strong wind is predicted on a wall of high - rise buildings, then the control system against the wind force is very important. It is examined by computer simulation. The actual wind data are given to the controller, and the responses are obtained and required characteristics are determined. By these considerations, a model was constructed and tested on the wall.

2. MECHANISM OF ROBOT

An example of conceptual model is shown in Fig.3. It has a long body and many wheels to get over the irregularities on a wall surface. A part of wheels can touch to the top of convex part on the wall, and the whole weight is supported by the vertical component of thrust force.

2.1 Thrustor.

A conventional thrustor is a combination of engine and propeller. A small jet engine and rocket motor can be available as the thrustors, but they are expensive and noisy compared with a conventioal one. There are two types of propellers ; those of a larger diameter one as a helicopter rotor and a smaller one as a light plane. The former can produce larger thrust force for the same engine power, but it is sensitive for wind gust, and the latter vice versa. From the reason, the latter is suitable for the robot which can move in the envoronment of strong wind. The required engine power of the latter is, however, larger, then the engine weight is heavier than the formar. Therefore the compromise of these conditions should be taken into account in the design phase.

2.2 A controller to compensate wind gust.

As the wind gust can not predict in advance, it is very difficult to compensate its effect by controlling the thrust force, since the control system has a time delay. If a robot has a larger thrust force, it must be safe by controlling it. However, it must be waste of excess thrust force and it means an increase of dead weight of the robot. About 20 % of thrust force margin is an appropriate value for both above consideration and engine characteristics, and it is given in the following calculations.

The thrust force controller is not enough to support the wind force acting on the robot as mentioned above, then a force without time delay is necessary. A frictional force augmentor is considered for this purpose, which is an airfoil and can produce the lift force to wall side to increase the frictional force of wheels. Its lift force is proportional to wind speed and does't have any time lag for wind velocity change, so it is a sensitive controller and actuator.

The wind gust has a wider friquency range, so that a higher frequency vibration appears by the wind force acting on the body and thrustor. To decrease it, a linear damper is effective. It is also considered as a controller, and it is installed between the body and wheels. Once the slipping of the robot begins on the wall, the coefficient of friction changes from static value to dynamic one, so that, it is very difficult to stop it within a short distance. A small slipping by the vibration is dangerous, therefore a damper is a helpful controller to decrease the danger.

As a whole, the wind force is compensated by a robot controller which consists of a thrust force controller, a frictional force augmentor and a damper.

2.3 Frictional force augmentor.

An example of augmentor and its characteristic are presented in Fig. 4. The maximum value of lift to drag force ratio is 4.2, and $L/D = 2$ is an appropriate value for an actual usage, since there is a small turbulence of wind velocity and direction on the wall surface of the buildings, and the lift force of augmentor depends on both of them directly. The angle of attack of augmentor is adjusted before moving the robot according to the assumed cross wind velocity and direction on the wall which the robot is going to move.

2.4 Control mechanism.

In order to control the robot on a wall, the magnitude of thrust force and its angles have to be controlled. The thrust force magnitude depends on the engine revolutional speed, i.e., engine throttle. Both angles of thrust force, parallel and vertical to the wall surface, are controlled.

The angle of wheels are also controlled in a same direction to move the robot on an inclined path. This is caused by the reason that it is dangerous to tilt the robot, when a mismatching occurs between the gravitational and thrust forces. There are two cases of moving, that is, with and without wheel drivings. For a case of wheel driving, a smaller thrust force is enough to move upward, however, the weight of driving mechanism is added, therefore this case is not always attractive. For a case of without wheel driving, a brake has to be installed.

3. CONTROL VARIABLES

3.1 Control variables of thrust force controller.

T,θ and ϕ are the control variables of thrust force controller, where T is the thrust force and angles θ and ϕ are shown in Fig.5. The robot controller, which consists of a thrust force controller, a frictional force augmentor and a damper, has to support the whole wind force, and must have a certain amount of surplus of supporting force for turbulent wind. The thrust force component of z − direction is taken as it, i.e., μT_z. By this assumption, the following relations can be derived as the force balance equations,

$$\text{on } y-\text{axis}, \qquad T_y = W \qquad (1)$$

$$\text{on } x-\text{axis}, \qquad T_x - D + \mu L = 0 \qquad (2)$$

and the supporting force is given as,

$$F_s = \mu\,(T_z + L\,) - \sqrt{(T_y - W)^2 + (T_x - D)^2} \qquad (3).$$

$F_s < 0$ means the beginning of slipping of the robot. Where W is the grvitational force, D the total drag force and $D = D_p + D_b$, and D_p is the drag force of propeller and D_b that of body and augmentor. L is the lift force of augmentor and μ is the coefficient of friction. T_x, T_y and T_z are the component of thrust force on x, y and z directions respectively, and they are given as follows.

$$\left.\begin{aligned} T_x &= T\sin\phi \\ T_y &= T\cos\phi\cos\theta \\ T_z &= T\cos\phi\sin\theta \end{aligned}\right\} \qquad (4)$$

The wind force on the propeller and body, D_p and D_b, can be represented as follows.

$$\left.\begin{aligned} D_p &= C_{DP}\,(1/2)\,\rho\,U^2\,S_p \\ D_b &= C_{Db}\,(1/2)\,\rho\,U^2\,S_b \end{aligned}\right\} \quad (5)$$

Where C_{DP} and C_{Db} are the drag force coefficients of propeller and body respectively. S_p is a circular disk area of propeller and S_b is a projected area of body and augmentor. The drag force of propeller depends on the inclined angle to the wind and C_{Dp} was measured by the wind tunnel testings, and given by the following experimental equations.

$$\left.\begin{aligned} C_{DP} &= a\lambda^b \\ a &= 0.02583 \times \exp(0.019\,\phi) \\ b &= -7.58 \times 10^5\phi^2 - 0.0108\,\phi + 1.203 \end{aligned}\right\} \quad (6)$$

Where $\lambda = V/U$, and V is the tip speed of propeller.

On the other hand, the thrust force of propeller depended on the wind velocity mainly, and is given by the following equation.

$$T = 0.0108\,\lambda^{2.109}\,(1/2)\,\rho U^2\,S_p \quad (7)$$

The drag force of propeller D_p can be expressed by the control variables of T and ϕ by combining Eqs. (6) and (7).

C_{Db} is a drag coefficient of body and augmentor. The former is assumed as unity for the frontal area of the body and the latter is given in Fig. 4 for the projected area of augmentor.

3.2 Characteristics of thrust force controller.

(1) The thrust force T depends on the revolutional speed of propeller, and its time dependent characteristic is assumed as a first order lag with a time constant of 0.2 (s) for an increase of wind speed and 0.15 (s) for a decrease of it, given by an experiment.

(2) The thrust force angle parallel to the wall surface ϕ is controlled by an ordinary servo − mechanism, and it has a constant angular velocity of 27 (deg/s) and delay time of 0.2 (s), which are given by the characteristics of actuator of the model.

(3) To simplify the control mechanism, another angle θ, vertical to the wall, is adjusted before moving the robot and it is taken as a parameter in the simulation.

3.3 Effect of frictional force augmentor.

The effect of augmentor is examined for the constant speed wind. Two examples of results are shown in Fig.6. In Fig. (a) a case of $L/D_b = 0$ is presented, which means none of the lift force is produced. In this case the robot is supported only by the thrust force component. In Fig. (b) $L/D_b = 2$ is given, which corresponds to $\mu L = D_b$ for $\mu = 0.5$, and it is shown that the robot can be supported in the wind speed of $U = 50$ (m/s), with both angles of $\theta = 10^\circ$ and $\phi_{max} = 32^\circ$.

From these figures it can be seen that the augmentor is effective for high speed wind.

3.4 A damper to reduce vibration.

It is assumed that a damper is installed between the body and wheels. Its natural circular frequency is given as $\omega_n = \sqrt{k/M} = 1$ (Hz), and the damping ratio is $\zeta = c/(2\sqrt{kM}) = 1$ is assumed. Where M is the mass of robot, k the spring constant and c the damping coefficient.

4. COMPUTER SIMULATION OF ROBOT CONTROLLER FOR TURBULENT WIND

To examine the performance of the robot, a model is considered, which has almost same specification as the one shown in Fig. 2. Its specification is given in Table 1.

Table 1. Specification of the model.

Total mass	$M = 20$ kg	Propeller diameter	0.6 m
Total thrust force	$(T/W)_{max} = 1.2$	Coefficient of friction	$\mu = 0.5$
Body length	1.8 m	Body width	0.9 m

4.1 Transient response of robot controller.

As the strong turbulence is involved in the wind gust, especially in the wind on a wall surface of high－rise buildings, it is very important to examine the response of robot controller to an abrupt change of wind speed. The step and ramp functions of wind speed are taken as the representatives. A few examples of results are given in Fig.7. For a step change of $U =$ 10～30 (m/s), the supporting force $F_s < 0$ appears at just after the step up and down of wind speed. This means the beginning of slipping of the robot and it must be avoided.

For a gradient of ramp function less than $\Delta U / \Delta t = 50$ (m/s^2), $F_s < 0$ doesn't appear.

4.2 Frequency response of robot controller.

The response of robot controller to a sinusoidal wind velocity change of $U =$ 10～30 (m／s) is examined. The results are shown in Fig.8. For an input frequency less than 0.5 (Hz), the controller can follow up the velocity change almost completely, so that the wind force can be compensated. On the other hand, for an input frequency higher than 4 (Hz) the damper can decrease the wind force remarkably. Therefore a frequency range from 0.5 to 4 (Hz) is important to the robot model. From the figure, the supporting force margin of 1 (Hz) is less than others, and this case is most dangerous.

All cases in Fig.8 are that for $\theta = 20°$, and the responses for other θ are calculated and shown in Fig.9. It can be seen that $\theta = 10°$ and 33.6° are dangerous, while $\theta = 20°$ and 30° are safe, i.e., each has a certain amount of suporting force margin.

4.3 Responses of robot controller to an actual turbulent wind.

A few examples of responses to an actual turbulent wind is shown in Fig.10. The wind speed changes at random within a range of $U =$ 5～40 (m／s) and the non－dimensional supporting force $F_s/W < 0$ appears for $\theta =$ 10° and 33.6° , not for $\theta = 20°$ and 30° . As F_s is difined by Eq.(3), the surplus of supporting force μT_z increases proportioal to θ, and $\theta = 30°$ has a good performance.

As $(T/W)_{max} = 1.2$ is assumed, ϕ_{max} decreases rapidly with increasing θ for the range of larger than $\theta = 30°$, so that the supporting force is also decreases and $F_s < 0$ appears for $\theta = 33.6°$, which is the maximum of θ and in this case ϕ is always zero.

It is shown by this figure that the robot controller which consists of a thrust force controller, a frictional force augmentor and a damper, can support the robot in a strong and turbulent wind safely.

5. MODEL TESTING

Several models have been constructed, and the recent one is shown in Fig.2. It has two thrustors and its total mass is about 18 (kg), and maximum thrust force is about 200 (N), so that, it can carry a small paylord.

A small wireless TV camera was installed and the wall surface was inspected on the groud. The navigation control was done by a radio controller through an onboard computer, and it was easy to move or stop on the wall surface in a weak wind or calm condition.

6. CONCLUSIONS

The basic investigation of a wall climbing robot is carried out, and the followings are concluded.

(1) At first the mechanism of robot is discussed. To compensate the wind force acting on the robot, the thrust force is controlled, and both a frictional force augmentor and a damper are used to give an additional supporting force.

(2) The characteristic of augmentor was examined by the wind tunnel testings and it is proved that it can support nearly a half of wind force for high speed wind of $U = 30 \sim 40$ (m/s).

(3) A transient response of the robot controller is examined by a step and ramp functions, and the supporting force $F_s < 0$ appears for the abrupt change of wind speed. These situations mean the slipping of the robot.

(4) A frequency response is also examined and it is shown that the frequency around 1 (Hz) is important for the model. For an input of sinusoidal wind speed change of $U = 10 \sim 30$ (m/s), and a frequency of 1 (Hz), a control variable $\theta = 30°$ has a better performance on a view point of supporting force margin.

(5) The response to an actual turbulent wind is also obtained, and it is shown that the robot can be supported in a turbulent and high speed wind of $U = 5 \sim 40$ (m/s) by controlling the thrust force.

(6) A robot model was constructed and tested on the wall to inspect the wall surface. It was proved that the robot model could be controlled easily by a radio controller through an onboard computer.

REFERENCES

[1] A. Nishi, Y. Wakasugi and K. Watanabe, "Design of a robot capable of moving on a vertical wall," Advanced Robotics, Vol.1, No.1, 1986, pp.33 – 45.

[2] A. Nishi, "Bipedal walking robot capable of moving on a vertical wall for inspection use," Proc. 5th Int. Symp. on Robotics in Construction, Vol. 2, 1988, pp.581 – 588.

[3] A. Nishi, M. Ohkura and H. Miyagi, "A robot capable of moving on a vertical wall using thrust force," Proc. IEEE Int. Workshop on Intelligent robot and systems, IROS'90, 1990, pp.455 – 463.

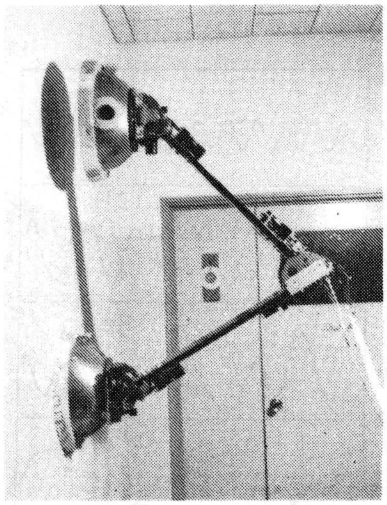

Fig.1. Biped locomotive model.

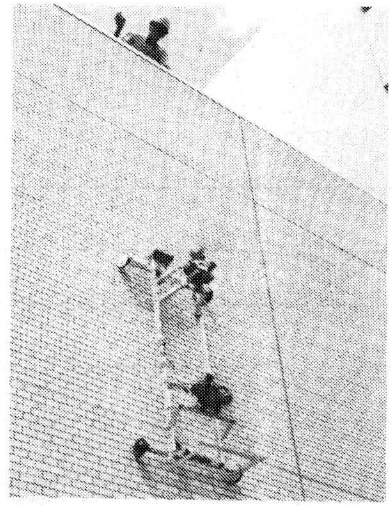

Fig.2. Present model.

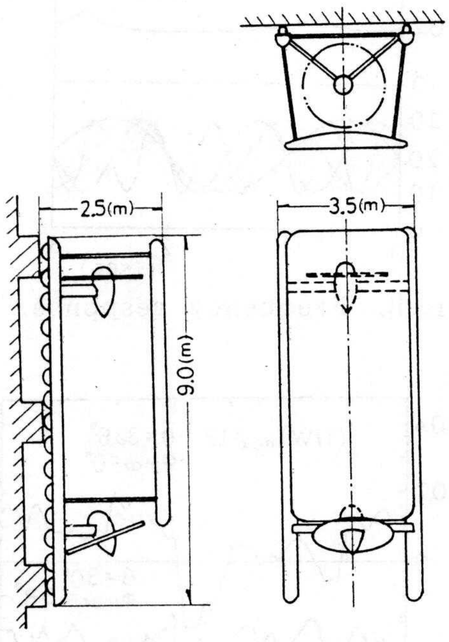

Fig.3. Conceptual model.

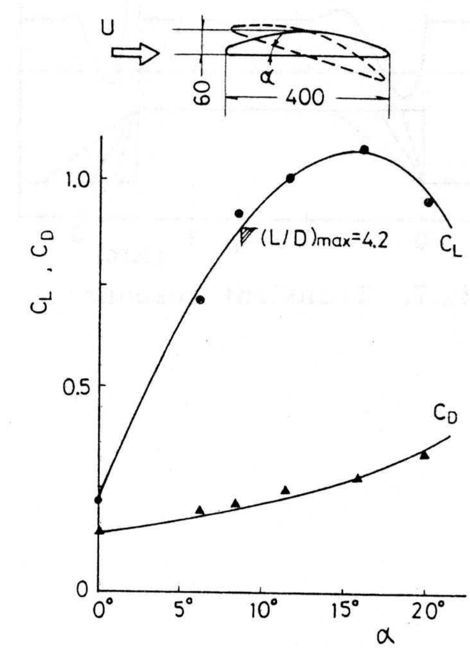

Fig.4. Augmentor characteristics.

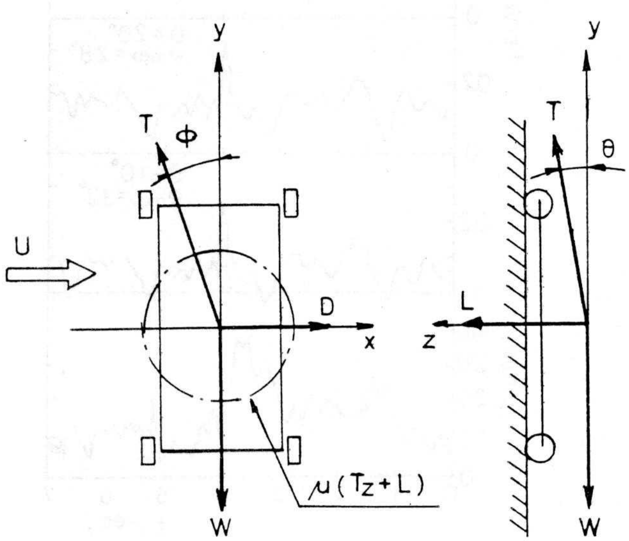

Fig.5. Coordinate system.

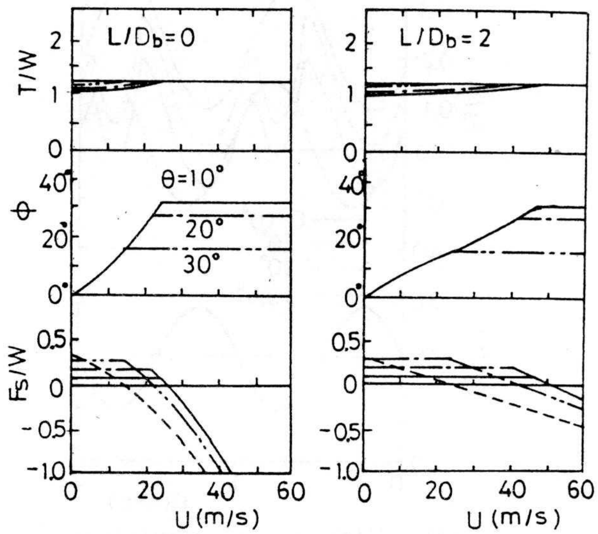

Fig.6. Effects of augmentor.

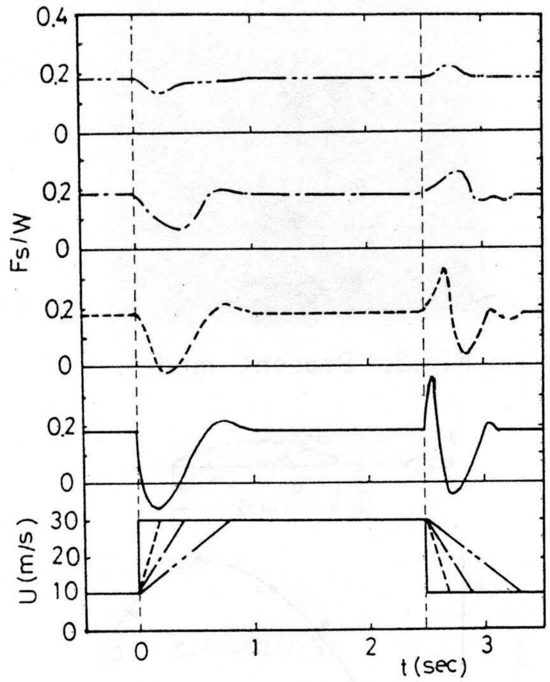

Fig.7. Transient response.

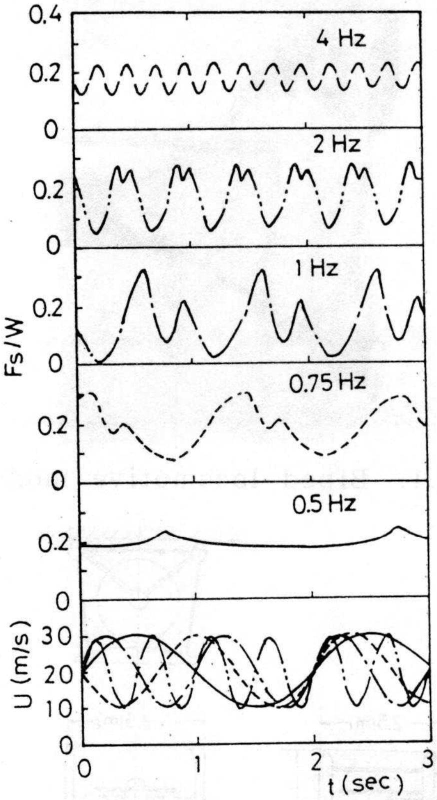

Fig.8. Frequency response.

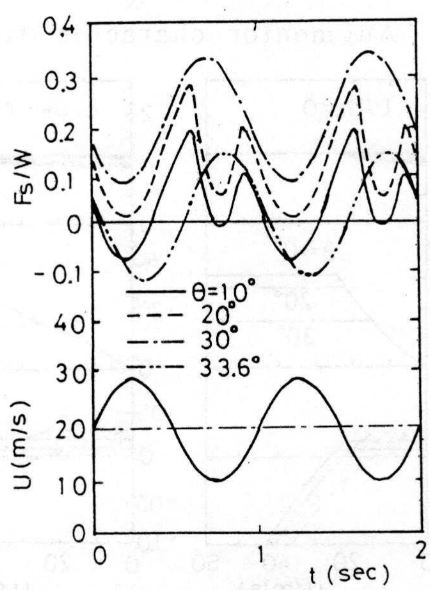

Fig.9. Effects of variable θ.

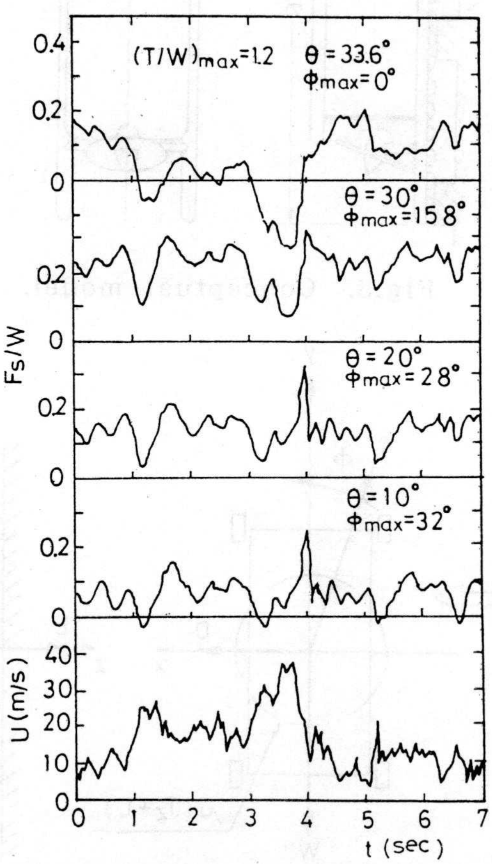

Fig.10. Response for actual wind.