

Rotation Speed Control of Horizontal-Axis Wind Turbine by Tip Vane*

Yukimaru SHIMIZU** and Shinji MATSUMURA**

This paper describes the rotation speed control of a horizontal-axis wind turbine. A tip vane has the excellent capability of improving the performance of the horizontal-axis wind turbine. Also, we found that the rotation speed of the wind turbine is controlled by changing the sweep angle of the tip vane. The relationships among the sweep angle of the tip vane, the change of wind speed and the rotor speed are investigated. As a result, a method to maintain constant rotor speed for changing wind speed, by means of an electromechanical apparatus, is developed.

Key Words: Fluid Machine, Horizontal-Axis Wind Turbine, Tip Vane Wind Turbine, Rotation Speed Control by Tip Vane, Braking Effect of Tip Vane

1. Introduction

The power augmentation of a horizontal-axis wind turbine having an equi-chord length and tapered blade with a tip vane, which is based on a unique idea by the present authors and co-workers, has been described in previous reports⁽¹⁾⁻⁽³⁾. In the past experiments, it was verified that the tip vane not only functions as a device for power augmentation of the wind turbine, but also induces a brake effect by means of changing SWEEP angle Λ (see Fig. 4) of the vane. This report describes the control of the rotor speed by changing the SWEEP angle. The results of the experiments clarified that it is possible to maintain constant rotational speed through SWEEP angle control in the case of a small fluctuation of wind velocity, while in the case of large fluctuation of wind velocity, pitch control of the main blade is also required.

2. Nomenclature

U : main flow velocity in wind tunnel [m/s]
 R : radius of rotor [m]
 T : torque arising from turbine rotation [N·m]

Ω : angular velocity of rotor [rad/s]

ρ : air density [kg/m³]

Λ : SWEEP angle of tip vane (See Fig. 4)
[degrees]

ζ : blade pitch angle [degrees]

ξ : inclination angle of wind turbine (See Fig. 4)
[degrees]

λ : tip speed ratio ($= R\Omega/U$)

C_p : power coefficient ($= T\Omega/0.5\rho U^3\pi R^2$)

3. Experimental Equipment and Method

In Fig. 1, the wind tunnel and the test wind turbine used in the experiment are shown. The wind turbine has two blades and is located at the position of 1.2 m (the diameter of the rotor) downwind from the outlet of the wind tunnel. The inside of the nacelle has a double axial construction: gear ⑤ connects with the rotor shaft and torque meter. In the lower shaft, the tachogenerator ⑦, torque meter ⑧ and electromagnetic brake ⑨ for load, which can be changed manually, are installed. The upper shaft is made of steel pipe. The signal of the stepping motor ④ is sent to the slip ring ⑥ through the shaft. The stepping motor is equipped with the boss of the turbine and connected to the tip vane ③ via a regulating rod. This stepping motor changes the SWEEP angle of the tip vane. At section ⑪, the tower of the wind turbine can

* Received 30th September, 1992. Paper No. 91-0611 A

** Department of Mechanical Engineering, Mie University, 1515 Kamihama-cho, Tsu-shi 514, Japan

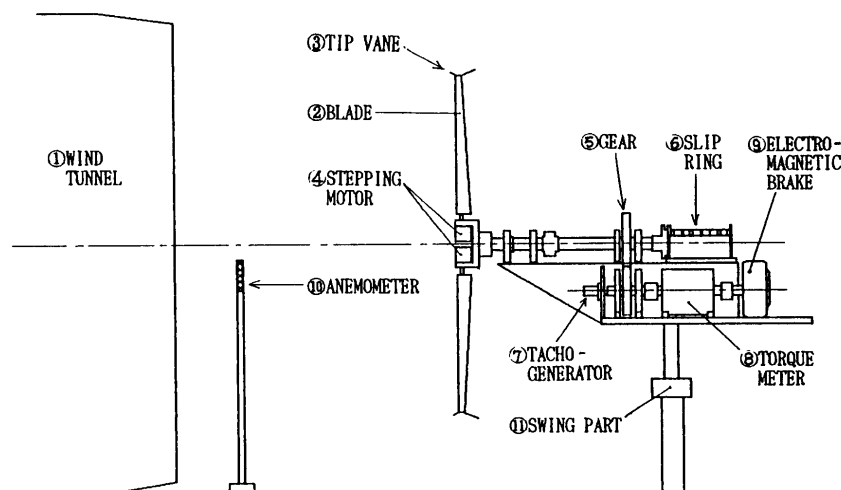


Fig. 1 Schematic diagram of experimental apparatus

Table 1 Specifications of blade

airfoil section	NACA4412
plane form of blade	taper twisted blade
material	wood-steel
length of blade	0.480 (m)
tip chord length	0.068 (m)
aspect ratio	5.714
taper ratio	0.083
radius of rotor blade	0.590 (m)

Table 2 Specifications of tip vane

Type	V(8*5.4)
A(C+D+E)	8.0 (cm)
B	5.4 (cm)
C	2.5 (cm)
D	4.5 (cm)
E	1.0 (cm)
α	15 (deg)
β	20 (deg)
Material	Steel

be manually rotated toward the wind direction.

The specifications of the blade used in the experiment are shown in Table 1. This blade has the NACA 4412 profile, and is twisted and tapered. The material of the blade is mainly balsa wood of which the surface is reinforced with reinforcing compound and finished smoothly.

Figure 2 shows the details of the tip vane, and the specifications are shown in Table 2. The material of the vane is aluminum plating of 2 mm in thickness. With the use of the V-type tip vane, which is 8 cm \times 5.4 cm, the highest power augmentation of the wind

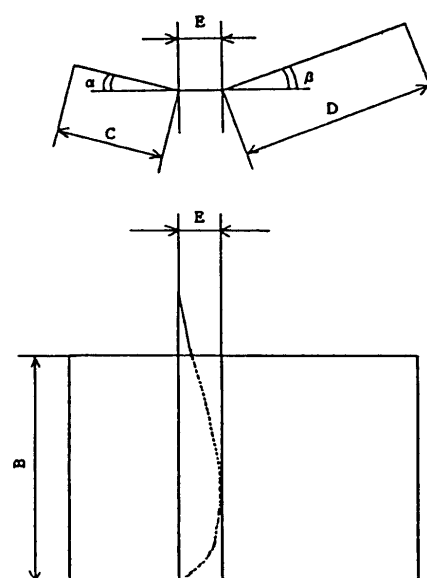


Fig. 2 Dimensions of test tip vane

turbine is achieved for all types of vane.

The anemometer is set at 80 cm upwind from the rotor plane, 20 cm to the right side and 10 cm below the rotating shaft.

Figure 3 shows the processing system for the data and the block diagram for the control signal for the stepping motor. The data of velocity, revolution of the wind turbine and torque are converted to signals less than DC 1 V, which pass through the A/D converter, and are subsequently processed by a small computer. After the recording, the processed data are input to the control loop, and then the control signal is sent to the stepping motor through the PPI board. This signal controls the stepping motor, after calculation and amplification in the driving device. The driving device is connected with a power supply of 15 V for the stepping motor and DC 5 V for the analog IC.

4. Brake Effect and Control Method of Tip Vane

SWEEP angle Λ of the tip vane, which is one of the installation angles of the blade, can be changed to various angles. As mentioned in the previous reports, when $\Lambda=0^\circ$, it is verified that C_p of the wind turbine with a tip vane is higher than that of a turbine without a tip vane. As can be seen in Fig. 11, Λ becomes larger with decreasing C_p . For the stepwise change of Λ , the tip vane works as a brake (or accelerator) for rotor rotation. Making use of this effect, an experiment to maintain constant rotational speed of the rotor was performed.

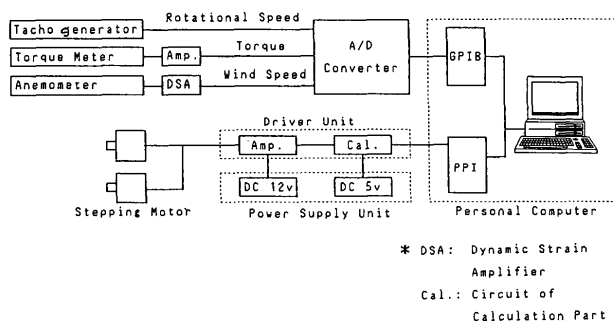


Fig. 3 Block diagram of input and output of signals

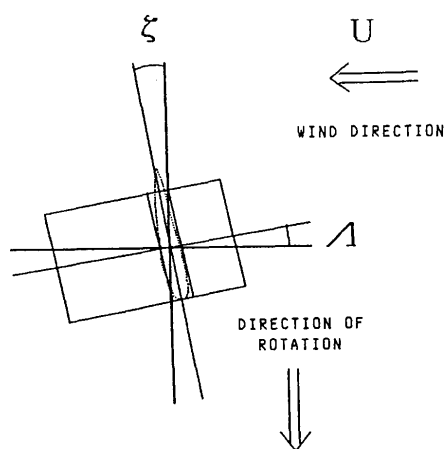


Fig. 4 Pitch angle ζ of main blade and SWEEP angle Λ of tip vane

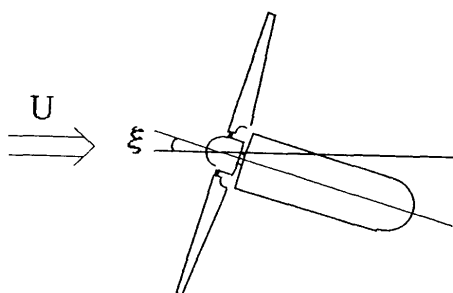


Fig. 5 Inclination angle ξ of wind turbine to wind direction

In this experiment, the controlled variable was the rate of change in Λ . The controlled variable Λ was determined from the difference R_e between the target of the rotational speed N_{aim} and instantaneous speed N_i , and from the time change ratio of A_c to R_e . The definitions of R_e and A_c are as follows:

$$R_e = N_i - N_{aim} \quad [\text{rpm}]$$

$$A_c = (N_i - N_{i-1}) / T_{\text{samp}} \quad [\text{rpm/s}],$$

where N_{i-1} is the rotational speed of the last control, N_i is the present speed and T_{samp} is the sampling time of the computer, which was 0.25 s in this experiment. In order to consider the controlled variable, we shall first discuss the change in rotational speed in unit time. In terms of R_{et} at an arbitrary time t and A_c , after a unit of time, R_{et+1} is

$$R_{et+1} = R_{et} + A_c.$$

In the case of $R_{et} + A_c = 0$, that is $R_{et+1} = 0$, SWEEP angle control is not needed. In the case of $R_{et} + A_c > 0$, after a unit of time, the rotational speed exceeds N_{aim} . In this case, brake control is needed, and the SWEEP angle becomes large. By contrast, in the case of $R_{et} + A_c < 0$, acceleration control is needed, because after a unit of time the rotational speed is lower than N_{aim} , and the SWEEP angle becomes small.

In practice, the rotation does not depend on these three conditions, because A_c is always changing, and there is a time lag of the control interval due to the sampling time of the computer. Since it is difficult to perform successive rotational control for that reason, the digital method of rotational control is carried out based on the three cases as mentioned above. To realize digital control, the $A_c = \Lambda$ diagram shown in Fig. 6 is empirically determined. The relationships between A_c (or R_e) and Λ needed for control are

$$|R_e + A_c| \leq 5: \text{no } \Lambda \text{ control region to avoid exceeding } N_{aim}$$

$$5 < |R_e + A_c| \leq 15: \Lambda = 0.9^\circ$$

$$15 < |R_e + A_c|: \Lambda = 3.6^\circ$$

In Fig. 7, the flow chart of the control program is shown for this experiment. As previously mentioned, the rotational speed (with wind velocity and torque)

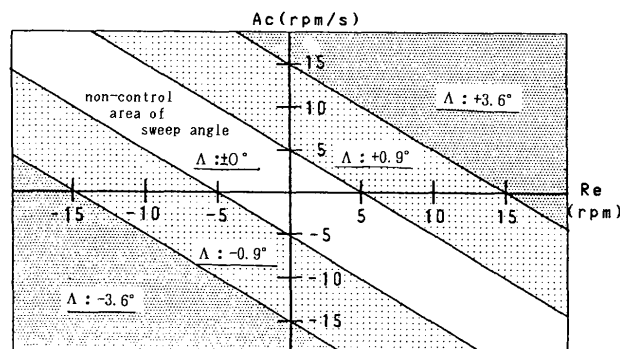


Fig. 6 Control map for SWEEP angle Λ of tip vane

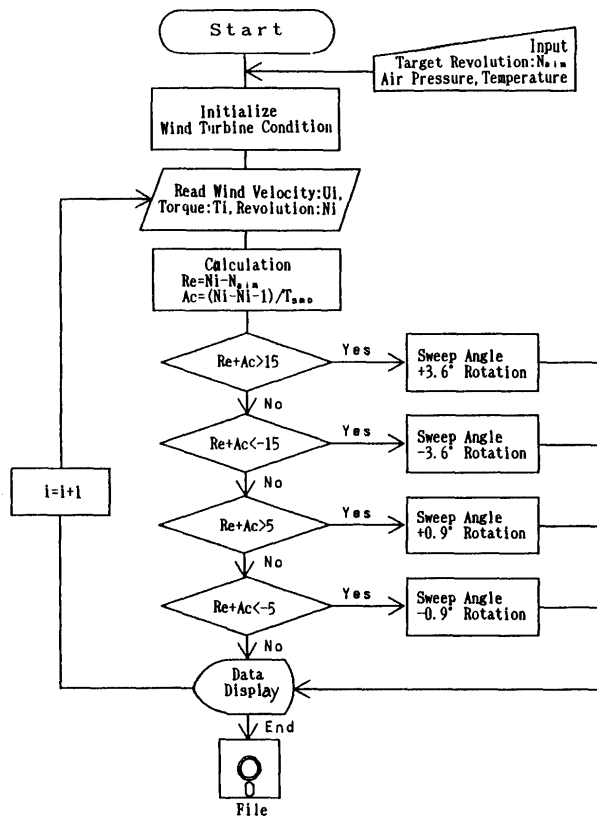


Fig. 7 Flow chart of control program

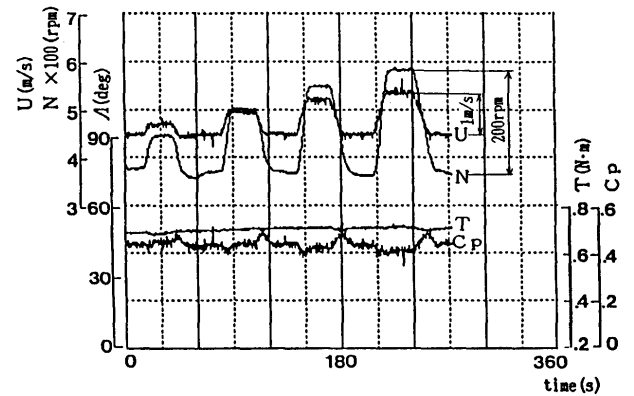
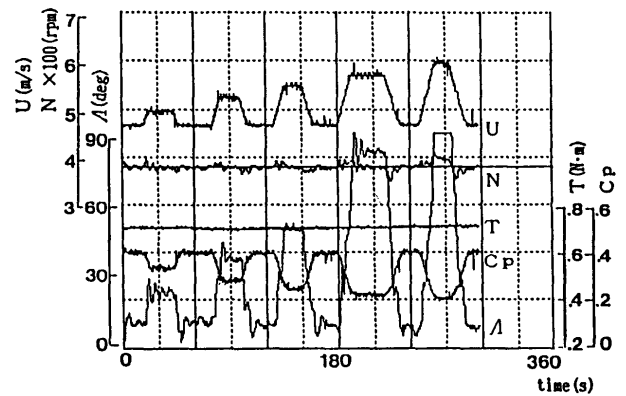
is sampled within 0.25 s. The program calculates R_e and A_c for the target N_{aim} and determines the controlled variable during the data input interval, then sends the signal to the stepping motor to change Λ .

5. Results and Discussion

5.1 Rotational control by changing SWEEP angle Λ

When the load is kept constant through the use of an electromagnetic brake, with fluctuating wind velocity, constant rotational speed control is achieved by means of SWEEP angle control.

Figures 8 and 9 show the rotational speed N_i , SWEEP angle Λ , torque T and performance C_p with fluctuating wind velocity in the cases of without Λ control and with Λ control, respectively. When the SWEEP control is not performed, the rotational speed increases to over 200 rpm, with the increase of the wind velocity to about 1 m/s. On the other hand, with Λ control, no fluctuation of the rotational speed occurs at all. In the case of increasing or decreasing wind velocity, the fluctuation of the rotational speed remains within ± 20 rpm, after which the wind velocity becomes constant, and rotational speed is maintained at N_{aim} . However, to a certain extent of increasing wind velocity (more than 5.9 m/s in this experiment), there is a region in which the rotational


Fig. 8 Dynamic characteristics of turbine output power in the case of no SWEEP angle control at $\zeta=1^\circ$ and $\xi=0^\circ$

Fig. 9 Experimental results with SWEEP angle Λ control, at $\zeta=1^\circ$ and $\xi=0^\circ$

speed exceeds N_{aim} even with the maximum SWEEP angle, $\Lambda=90^\circ$, which is the most acceptable brake effect of the vane.

In such a case, additional pitch angle control of the blade is required for excessive velocity. The wind turbine used in this experiment does not have mechanical pitch angle (defined ζ : see Fig. 4) control of the blade; thus ζ is changed manually. Figure 10 shows the results of Λ control in the case of $\zeta=9^\circ$. Although at $\zeta=1^\circ$ control is impossible for wind velocity exceeding 5.9 m/s, at $\zeta=9^\circ$, the rotational speed can be decreased. Figure 12 shows the performance curve of the wind turbine with $\zeta=9^\circ$. In both Fig. 11 and Fig. 12, the dashed line represents the performance for λ in the case of constant revolution ($N_{aim}=380$ [rpm]), which is the same as constant torque operation ($T=0.7$ [N·m]). The single-point line shows the wind velocity derived from λ at $N_{aim}=380$ [rpm]. If we compare the results of $\zeta=1^\circ$ (Fig. 11) and $\zeta=9^\circ$ (Fig. 12), it is clear that the region of λ with $\zeta=9^\circ$ is lower than that with $\zeta=1^\circ$. At $\zeta=1^\circ$ under $U=5.5$ [m/s], the wind turbine can rotate at 380 rpm; however, at $U=6.0$ [m/s], it cannot rotate because this is the stall

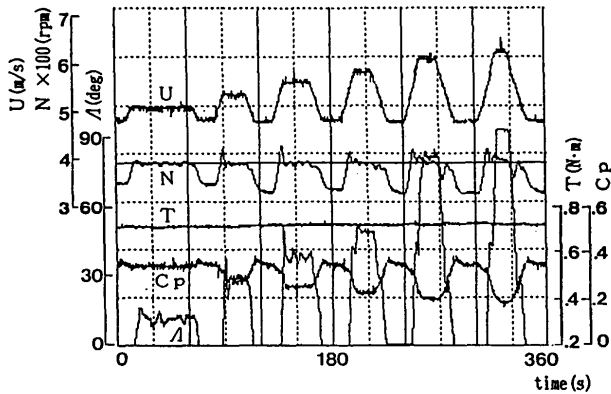


Fig. 10 Experimental results with SWEEP angle Δ control, at $\zeta=9^\circ$ and $\xi=0^\circ$

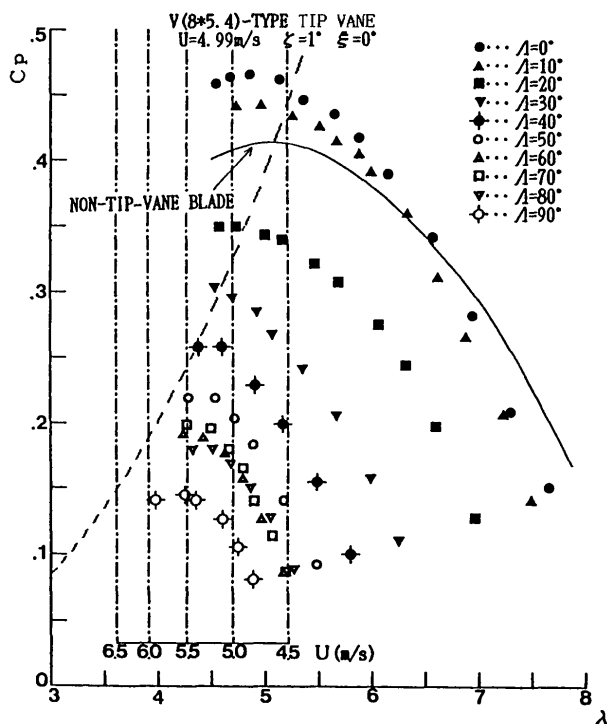


Fig. 11 Relationship between power coefficient C_p and tip speed ratio λ , with SWEEP angle Δ changes at $\zeta=1^\circ$

region. At $\zeta=9^\circ$, it can rotate at 380 rpm even if $U \geq 6.0$ [m/s], but not at 380 rpm and U of approximately 5.0 m/s. These data respectively correspond with the results of the control in Figs. 9 and 10.

Based on the above, for rotational control of the wind turbine, SWEEP angle control is a suitable method for small fluctuations of wind velocity within the domain of ± 1 m/s. However, with excessive velocity, additional control, for instance, pitch angle control of the main blade, is required.

5.2 Rotational control in slanted inflow

In the field, wind does not always flow perpendicular to the rotating plane of the wind turbine. For that

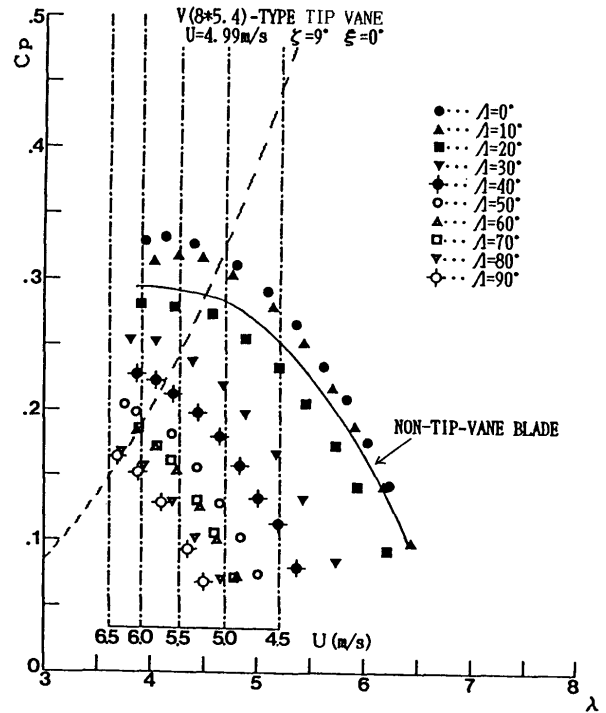


Fig. 12 Relationship between power coefficient C_p and tip speed ratio λ , with SWEEP angle Δ changes at $\zeta=9^\circ$

reason, we empirically consider the applicability of SWEEP angle control for inflow slanted with respect to the rotating plane.

In slanted inflow, the resultant velocity of the axial and tangential velocities depends on the azimuth angle of the blade. It has been verified that, independent of the tip vane, C_p decreases in proportion to increase of the inclination angle ξ , the region of λ over the entire range of ξ becomes lower, and power augmentation is achieved by use of the tip vane (see Ref. (1), section 4.5). Figure 13 shows the relationship of C_p to Δ with $\xi=15^\circ$. In this case, C_p also decreases depending on the increase of Δ , and furthermore, the reduction rate of λ for changing Δ becomes larger than that at $\xi=0^\circ$. Consequently, rotational speed control with constant output power may be possible within the stable region of the wind turbine.

Figures 14 to 16 show the results of $\xi=15^\circ$, 30° and 45° with Δ control. These figures show the possibility of rotational control through the SWEEP angle in slanted inflow. For ξ becoming larger and larger, the rotational control is possible with small Δ for the same rate of increase of the velocity as in the case of straight inflow. Provided that $\xi=15^\circ$, the rotational speed does not converge and remains in the oscillation state, i.e., the area enclosed by the dot-dash line in Fig. 14. The following reasons are considered. First, in the region of Δ from 50° to 90° , rotation

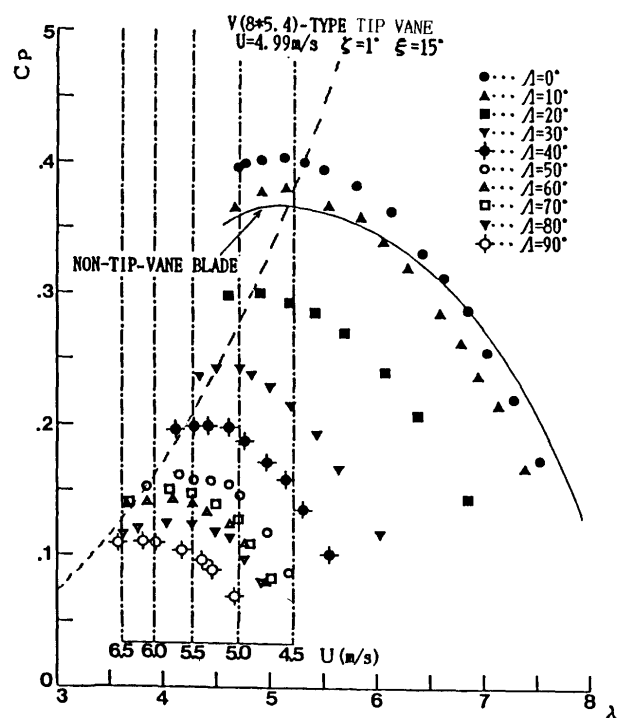


Fig. 13 Relationship between power coefficient C_p and tip speed ratio λ , with SWEEP angle Δ changes at $\xi=15^\circ$

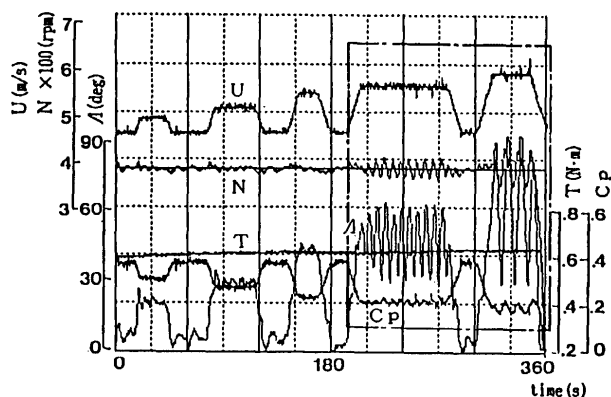


Fig. 14 Relationship between SWEEP angle Δ and control for rotational speed at $\xi=15^\circ$ and $\zeta=1^\circ$

at 380 rpm is very unstable because the blade easily stalls. Second, the decrease in the performance is depend on Δ , and especially with $\Delta=70^\circ$, higher performance than is observed with 60° . Consequently, the rotational speed exceeds the target revolution in spite of SWEEP angle control.

According to these results, to realize revolution control, the control region must be set on the basis of this phenomenon. The prediction of velocity fluctuation will become an important factor for achieving precise control.

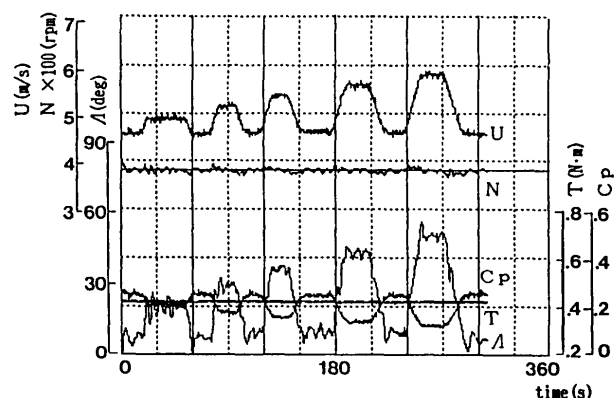


Fig. 15 Relationship between SWEEP angle Δ and control for rotational speed at $\xi=30^\circ$ and $\zeta=1^\circ$

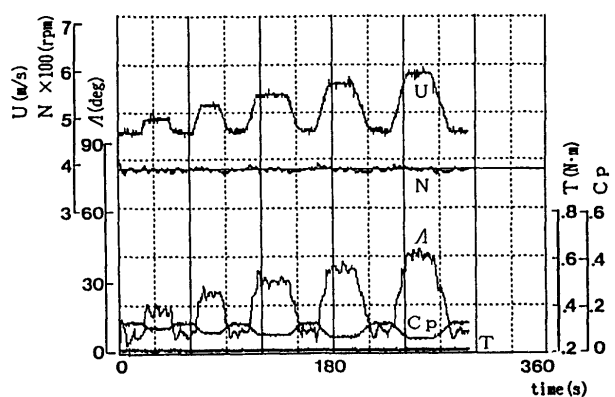


Fig. 16 Relationship between SWEEP angle Δ and control for rotational speed at $\xi=45^\circ$ and $\zeta=1^\circ$

6. Conclusions

- (1) SWEEP angle control of the tip vane enables us to keep the rotational speed of the wind turbine constant.
- (2) In the case of large fluctuation of wind velocity, combining pitch control of the blade with SWEEP angle control gives a good solution.
- (3) In slanted inflow, the rotational speed can also be kept constant by means of SWEEP angle control.

References

- (1) Shimizu, Y., Yoshikawa, T. and Matsumura, S., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 56, No. 522, B (1989), p. 495.
- (2) Shimizu, Y., Yoshikawa, T. and Kajimoto, K., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 56, No. 522, B (1989), p. 502.
- (3) Shimizu, Y., Matsumura, S. and Imamura, H., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 57, No. 543, B (1991), p. 3845.