Overspeed Control of a Variable-Pitch Vertical-Axis Wind Turbine by Means of Tail Vanes*

Tatsuro YAMADA**, Takahiro KIWATA***, Tetsuyoshi KITA****, Masao HIRAI***** and Takaaki KONO***

**Assembling Shop No. 2, Production Dept., Machine Tool Div., Mitsubishi Heavy Industries, Ltd.
Ritto, Shiga 520-3080, Japan
E-mail: tatsuro_yamada@mhi.co.jp

***Research Center for Sustainable Energy and Technology, Kanazawa University,
Kakuma-machi, Kanazawa-shi 920-1192, Japan

****Betsukawa Corporation, Hakusan-shi 924-8560, Japan

*****School of Mech. Eng., Kanazawa University, Kakuma-machi, Kanazawa-shi 920-1192, Japan

Abstract

This paper describes the overspeed control of a vertical-axis wind turbine (VAWT) without an electric control system or mechanical brakes. To improve its performance with straight blades, a VAWT with a variable-pitch mechanism consisting of a four-bar linkage was designed. This wind turbine exhibits directivity to the wind, which is able to make use of rotational speed control in a VAWT. This wind turbine can achieve passive yaw control by means of tail vanes, which are installed on the eccentric link lever. The yaw angle characteristics of the tail vanes were measured in an open-circuit wind tunnel and in field tests. The yaw angle variations from the numerical analysis are in good agreement with the experimental data from the wind tunnel tests. It was found that overspeed prevention by means of tail vanes is useful in protecting a VAWT from strong winds without using mechanical brakes.

Key words: Vertical-Axis Wind Turbine, Wind Energy, H-type Darrieus Wind Turbine, Variable Pitch, Tail Vane, Rotational Speed Control

1. Introduction

Since wind power generation emits no carbon dioxide, the use of wind energy has recently attracted considerable attention in the prevention of global warming. Therefore, the private development of micro wind power generation technologies has increased over the years. However, it is necessary to improve the safety, reliability, and cost performance of the micro wind turbines used to generate electricity so that wind power generation may expand further (1)-(3).

Wind turbines are classified according to the orientation of their axis of rotation: namely, horizontal-axis wind turbines (HAWTs), and vertical-axis wind turbines (VAWTs) (4)-(6). A VAWT with straight blades (i.e., an H-type Darrieus wind turbine) is a lift-force type of wind turbine. Advantages of the VAWTs include their independence of the wind direction for their operation and noise levels not exceeding those of HAWTs. However, at low wind speeds, the Darrieus wind turbine is slow to self-start and has poor output due to cyclical
variations in the large-amplitude angle of attack. In addition, a Darrieus wind turbine cannot control its rotational speed by controlling the pitch angle of its blades like a propeller-type wind turbine can (7)-(9). If the brake system malfunctions in strong winds, the wind turbine will rotate too fast and get damaged by the centrifugal force. Therefore, overspeed is one of the most important problems for wind turbines, and a mechanical or electromagnetic brake system is necessary for rotational speed control of Darrieus wind turbines during strong winds.

Small turbines sometimes use mechanical brakes that are activated by drag or centrifugal force (9). For propeller-type wind turbines, aerodynamic brake systems like pitchable blade tips, deployable spoilers, and flaps are used as passive speed control devices (10)-(12); also, passive yawing systems that continuously change the yaw angle of the rotor by wind pressure beyond a certain wind speed protect the wind turbine during strong winds by averting the turbine rotor from the wind direction (10). Aerodynamic brake systems do not stop the rotor completely but reduce its rotational speed to a safe value. Deployable spoilers are often used with Darrieus wind turbines. However, the unsynchronized activation of the brakes for different blades is an unwelcome side-effect as it causes an aerodynamic imbalance and has caused damage to some turbines. Noda et al. (13) proposed an H-type Darrieus wind turbine with a rotational overspeed inhibition mechanism using self-control of the pitch angle when its rotational speed exceeds the upper limit. They showed that this wind turbine can operate without rotational overspeed in strong winds. The ASI/PINSON wind turbine is one H-type Darrieus wind turbine with a variable pitch angle mechanism, and it has an overspeed prevention device that operates in conjunction with a tilt cam and a V-shape tail vane (14).

The authors developed an H-type Darrieus wind turbine with a variable pitch angle mechanism using a four-bar linkage (15). This mechanism makes it relatively easy to control the pitch angle of the straight blades without actuators. The power coefficient of this VAWT is better than one with fixed-pitch blades. One feature of this wind turbine is the directivity to the wind, which is able to make use of the rotational speed control in H-type Darrieus wind turbines. If a wind turbine has to operate under high rotational speeds, the position of the lever should be kept at an eccentric angle $\theta_p = 0^\circ$ to the wind direction. Additionally, this turbine can stop its rotation by means of the eccentric link lever at an eccentric angle $\theta_p = 90^\circ$ or $270^\circ$ to the wind direction. This characteristic can be used to protect the wind turbine from strong winds without using mechanical brakes.

Our aim is to develop a passive rotational speed control device using the wind directivity of a VAWT with variable-pitch blades. This paper describes the performance of a variable-pitch VAWT with single and double tail vanes installed on the eccentric link lever. The proposed double tail vanes consist of a main tail vane and a sub tail vane with a flap. This device makes use of the difference between the aerodynamic moments of the main and sub vanes above a certain wind speed, and the angle of the eccentric lever is changed passively by the wind force. The effects of the size and location of the tail vanes on the performance of the wind turbine were examined in an open-circuit type wind tunnel and in field tests. The possibility of an overspeed prevention device by means of double tail vanes during strong winds was also investigated using experimental and numerical analyses.

2. Variable Pitch Angle Mechanism and Overspeed Prevention Device for VAWT with Straight Blades

2.1 Variable pitch angle mechanism and turbine rotor

Figure 1 shows a top view of the rotor and variable pitch angle mechanism of the developed VAWT with straight blades. Figure 2 shows an overview of the wind turbine. The rotor, which had three straight blades, has a diameter of $D = 0.8$ m and a height (blade span
length) of $h = 0.8$ m. The variable pitch angle mechanism is a four-bar linkage. This mechanism is able to vary the blade's pitch angle $\alpha_p$ according to the rotation of the wind turbine without actuators. This rotor has an eccentric rotational point $O_e$ that is different from the main rotational point $O$. The angle between the main link $l_m$ and the eccentric link $l_e$ is the blade azimuth angle $\varphi$, and $\theta_p$ is the eccentric angle, i.e., the angle between the eccentric link and the X-axis (wind direction). The eccentric angle $\theta_p$ corresponds to the yaw angle $\phi$ of the propeller-type wind turbine (i.e., $\theta_p \approx \phi$). The blade offset pitch angle $\alpha_c$ is changed by changing the length of the second link $l_s$, and the blade pitch angle amplitude $\alpha_w$ is changed by changing the eccentric link length $l_e$. More detailed information on the characteristics of the variable pitch angle mechanism using a four-bar linkage is referred to in our previous work (15). In this experiment, the conditions of the blade pitch angle amplitude $\alpha_w (\approx \pm 15.0^\circ)$ and the blade offset pitch angle $\alpha_c (\approx 11.9^\circ)$ at the maximum power coefficient were adopted (15).

2.2 Overspeed prevention system

To passively control the rotational speed of turbines, the double tail vane system shown in Fig. 3 was proposed. The main tail vane was installed on the eccentric link lever (length $L_m$). The sub tail vane was attached to the second shaft (length $L_s$) with the main tail vane. The interval angle $\theta_i$ is the angle between the lever of the sub tail vane and the lever of the main tail vane. The sub tail vane has a flap, the initial flap angle $\alpha_{flap}$ of which can be arbitrarily set. For a weak wind, the flap does not rise up, and the position of the eccentric rotational point $O_e$ depends only on the main tail vane, which follows the wind direction.
(i.e., $\theta_p \approx 0^\circ$). On the other hand, under a strong wind, the flap rises up, and the eccentric angle $\theta_p$ changes to a different angle ($\theta_p \neq 0^\circ$) due to the rotary torque of the sub tail vane.

3. Experimental Apparatus and Numerical Analysis Methods

3.1 Wind tunnel tests

A schematic diagram of the experimental apparatus is shown in Fig. 4. As shown in Fig.4(a), the experiment was performed in an open-circuit wind tunnel with a 1400 mm-long working section and a square cross-section of 1200×1200 mm$^2$. The turbulence intensity and the nonuniformity level of the velocity at the exit of the nozzle at a wind speed of $V = 6$ m/s were less than 0.8% and ±1.8%, respectively. The wind turbine was set up at the center of the square cross-section of the wind tunnel. The blades had chord lengths of $c = 0.2$ m and NACA634-221 airfoil sections and had an aluminum monocoque structure with thin plates (thickness: 0.5 mm) and frames. The single (main) tail vane was installed on the eccentric link lever. The specifications of the tail vanes are shown in Fig.4(b). The vanes consisted of hollow aluminum pipes with a diameter of 12 mm and aluminum boards with a thickness of 2.0 mm. As shown in Fig. 4, a three-phase induction motor (Mitsubishi Electric, SB-JR 2.2kW 4P) was used to drive the turbine. To observe the behavior of the power coefficient at a given the tip speed ratio (TSR) $\lambda$, the frequency of the motor was varied using an inverter (Hitachi, SJ200). The torque $T$ and the rotational speed $N$ of the turbine were measured using a torque transducer (TEAC, TQ-AR5N) and a digital tachometer (ONOSOKKI, HT-5500) to calculate the power coefficient $C_p$ ($=2\pi NT/(60\rho RV^3)$) in each case. The uniform flow $V$ in the working section was measured using a Pitot-static tube and a thermal anemometer (KANOMAX, Climomaster model 6531). The angle of the tail vane (eccentric angle $\theta_p$) was measured using a protractor.

Figure 5 shows the experimental apparatus for the measurement of the fluid force on the flat plates. To calculate the yawing motion of the double tail vanes, the complete lift and drag characteristics of rectangular flat plates with aspect ratios of $AR = 0.5$, 1.0, and 2.0 were measured using a load cell (Nissho Electric Works, LMC-3505-100N) and a DC amplifier (Nissho, DSA-100A-6ch). The uniform flow velocity was $V = 5$, 10, and 15 m/s. The Reynolds number based on the chord length $c = 200$ mm was changed from $Re = 6.7 \times 10^4$ to $2.0 \times 10^5$. The angle of attack was varied in the range of $0^\circ \leq \alpha \leq 180^\circ$.

Figure 6 shows a schematic diagram of the sub tail vane with a flap to examine the relationship between the initial flap angle $\alpha_{flap}$ and the wind speed needed to raise the flap. The flap is connected to the base of the sub tail vane with a hinge. The initial flap angle $\alpha_{flap}$ is able to change based on the length of the strings. The flap is an aluminum plate with a width of 0.3 m and a length of 0.2 m (aspect ratio: $AR = 1.5$). The plate thicknesses are 1.0 mm and 0.5 mm, and the plate weights are 160 g and 80 g. Additionally, as shown in Fig. 7, the yawing motion of the double tail vanes without the rotor was also studied in the wind tunnel. The rotational speed and the angle of the tail vanes (eccentric angle $\theta_p$) were measured using a rotary encoder (Copal Electronics, JT30-340-500). Assuming the flap rises up in a strong wind, i.e., a vertical flat plate ($\alpha_{flap} = 90^\circ$), the effects of the lever lengths and areas on the yawing motion of the double tail vanes were investigated.

3.2 Field tests

The feasibility of rotational control by means of double tail vanes was examined in a field test. To examine the effect on the turbine rotational speed by the yaw motion of the double tail vanes, the turbine was run under zero-load condition which is gotten maximum turbine rotational speed. As shown in Fig. 8, the rotational speed of the wind turbine, the main tail vane direction, the wind direction, and the wind speed were measured using a digital tachometer, a laser displacement sensor (KEYENCE, LB-01), and a propeller-type
anemometer with a tail wind vane (R. M. Young Company, No. 7270-20), respectively. The wind speed at which the flap rises up can be arbitrarily set by changing the flap’s initial angle of attack \( \alpha_{\text{flap}} \) and thickness (weight), as shown in Fig. 6.

### 3.3 Numerical analysis of the motion of double tail vanes

To fulfill these essential qualifications, the behavior of the double tail vanes (i.e., the time histories of the eccentric angle \( \theta_p \) and yawing angular velocity \( \omega_p \)) were predicted, and...
the effects of the length ratio of the levers \( L_s/L_m \) and the area ratio of the tail vanes \( A_s/A_m \) were examined by numerical analysis. The motion equation of the torsional vibration for the double tail vane system is as follows:

\[ I_v \frac{d^2 \omega_p}{dt^2} + f \omega_p = M_{Rm} + M_{Rs} \]

(1)

where \( I_v \) is the inertia moment of the whole tail vane system, \( f \) is the damping coefficient, \( \omega_p \) (\( = \frac{d\theta_p}{dt} \)) is the yawing angular velocity of the tail vanes, \( M_{Rm} \) is the rotational moment from the main tail vane, and \( M_{Rs} \) is the rotational moment from the sub tail vane. \( M_{Rm} \) and \( M_{Rs} \) are calculated as follows:

\[ M_{Rm} = C_{Rm} \frac{1}{2} \rho A_m \left( V \sin \theta_p - \omega_p L_m \right)^2 \cdot L_m \]

(2)

\[ M_{Rs} = C_{Rs} \frac{1}{2} \rho A_s \left( V \cos \theta_p + \omega_p L_s \right)^2 \cdot L_s \]

(3)

where \( \rho \) is the air density, and \( C_{Rm} \) and \( C_{Rs} \) are the restoration coefficients of the main tail vane and the sub tail vane, respectively. The restoration coefficients \( C_{Rm} \) and \( C_{Rs} \) are calculated from the eccentric angle \( \theta_p \), the lift coefficient \( C_L \), and the drag coefficient \( C_D \) of the flat plate as follows:

\[ C_{Rm} = C_L \cos \theta_p + C_D \sin \theta_p, \quad C_{Rs} = C_L \cos \theta_p + C_D \sin \theta_p \]

(4)

The lift coefficient \( C_L \) and the drag coefficient \( C_D \) of a low-aspect-ratio flat plate were measured in the wind tunnel test. The Runge-Kutta method was used to solve the difference equation (Eq. (1)), and the time histories of the yawing angular velocity \( \omega_p \) and the eccentric angle \( \theta_p \) were calculated.

4. Results and Discussion

4.1 Wind directivity of the wind turbine

The wind directivity of the wind turbine with the variable pitch angle mechanism was investigated in the wind tunnel. Figure 9 shows the variation in the rotational speed \( N \) of the wind turbine against the eccentric angle \( \theta_p \), i.e., the angle between the eccentric link and the wind direction under the zero-load condition at \( V = 5 \) m/s. The rotational speed of the wind turbine depends on the eccentric angle \( \theta_p \). At \( \theta_p > 55^\circ \) or \( < 315^\circ \), the rotational speed decreases. At \( \theta_p = 70^\circ \) or \( 270^\circ \), the rotation of the wind turbine stops. Therefore, the rotation of the wind turbine can be controlled by adjusting the position of the eccentric link lever.

Figure 10 shows the effect of the eccentric angle \( \theta_p \) on the power coefficient \( C_p \). The power of the variable-pitch VAWT depends on the eccentric angle \( \theta_p \). The power coefficient for the eccentric angle \( \theta_p = 0^\circ \) is larger than that for the other eccentric angles. The
maximum power coefficient of the eccentric angle \( \theta_p = 0^\circ \) is \( C_P = 0.228 \). Variations in the power coefficient ratio \( C_P / C_{P\theta_p=0^\circ} \) for the propeller wind turbine and the present wind turbine with the yaw angle \( \theta_p \) are shown in Fig. 11. According to data from Imamura et al. \(^{16} \), the power coefficient of the propeller wind turbine decreases as a function of \( \cos^2 \theta_p \). Although the variable-pitch VAWT has directivity to the wind like the propeller wind turbine, the power coefficient of the present wind turbine is less sensitive to the yaw angle than that of the propeller wind turbine. The power coefficient ratio of the variable-pitch VAWT decreases as a function of \( \cos(17\theta_p/20 + \pi/20) \).

### 4.2 Effects of area and location of the single tail vane

To follow the wind direction and operate at maximum rotational speed, a single tail vane was installed on the eccentric link lever that was not fixed on the protractor plate. Figure 12 shows the effects of the area of the single tail vane on the power coefficient \( C_P \).
and the eccentric angle $\theta_p$ at $V = 8$ m/s. The difference between the maximum power coefficient of the centrally located standard tail vane and the fixed tail vane at $\theta_p = 0^\circ$ is small in comparison with the small tail vane. The eccentric angle $\theta_p$ increases with an increase in TSR $\lambda$ (i.e., the rotational speed) within $\theta_p = 30^\circ$. The variation in the eccentric angle $\theta_p$ relates to the balance between the rotary torque that is transmitted from the main shaft of the wind turbine to the second shaft and the aerodynamic force that acts on the tail vanes (the restoring torque). For the wind turbine without a vane plate, the eccentric angle $\theta_p$ increases rapidly with an increase in TSR $\lambda$, but it is very interesting that the present variable-pitch VAWT can rotate without a tail vane.

Figure 13 shows the effect of the tail vane location on the power coefficient. The maximum power coefficient of the upper-located tail vane is slightly smaller than those of the centrally located and lower-located tail vanes. The restoring force of the upper-located tail vane decreases because the upper part of the tail vane is located in the wake region of the wind turbine, so the eccentric angle $\theta_p$ increases with an increase in TSR $\lambda$ (as shown in Fig. 13(b)). However, the influence on the power coefficient decrease is $2\%$ or less. The location of the tail vanes has an insignificant effect on the power coefficient, with the exception of the upper-located tail vane condition.

4.3 Yawing motion of the double tail vanes

To predict the behavior of the tail vanes numerically, the lift and drag coefficients of the...
low-aspect-ratio flat plate were measured by the wind tunnel test. The complete lift and drag characteristics of the flat plate for aspect ratios of $AR=0.5$, $1.0$, and $2.0$ are shown in Fig. 14(a) at velocities of 5, 10, and 15 m/s. A comparison of characteristics of the $AR=2.0$ flat plate with past data is also shown in Fig. 14(b). The lift and drag coefficients for $0° \leq \alpha \leq 60°$ agree with the data from Gabriel et al. (17) and Matsumiya et al. (18). So, the present lift and drag coefficient data for the flat plate presented in Fig. 14(a) were used to calculate the yawing motion of the double tail vanes.

Figure 15 presents the yawing motion of the double tail vanes without the rotor, as shown in Fig. 7. The two tail vanes have a lever length ratio of $L_s/L_m = 1.0$, a tail vane area ratio of $A_t/A_m = 1.0$, and an interval angle between the two tail vanes of $\theta = 90°$. The flap angle $\theta_{flip}$ of the sub tail vane was a constant $90°$ (i.e., a vertical flat plate). The inertia moment of the whole tail vane system was $I_v = 1.25 \text{ kg m}^2$, and the damping coefficient was $f = 3.78 \text{ N m s}^{-1}$. The initial angle of the main tail vane was $\theta_p = 0°$. The wind speed was changed between $V = 5, 10,$ and $15 \text{ m/s}$. There is good agreement between the results of the wind tunnel test and the numerical analysis. Both the experimental and numerical results yield a steady-state value of $\theta_p = 45°$. Thus, this result shows that the behavior of the tail vanes can be estimated numerically using the motion equation for torsional vibration.

Figure 16 shows the effects of the lever length ratio $L_s/L_m$ and area ratio $A_t/A_m$ on the steady-state eccentric angle and the maximum angular velocity for the yawing motion of the double tail vanes. The condition of $L_s/L_m \geq 2.0$ and $A_t/A_m \geq 1.0$ is able to achieve an eccentric angle of $\theta_{p, steady} \geq 55°$, which decreases the rotational speed of the wind turbine, as shown in Fig. 9. Although the maximum angular velocity $\omega_{p, max}$ (19) for $L_s/L_m = 1.0$ is

(a) Steady-state eccentric angle $\theta_{p, steady}$

(b) Maximum yawing angular velocity $\omega_{p, max}$

Fig.16 Effects of the lever length ratio $L_s/L_m$ and area ratio $A_t/A_m$ on the yawing motion of the double tail vanes ($\theta = 90°$)

Fig.17 Relationship between the initial flap angle $\alpha_{flip}$ and the wind speed $V$ at which the flap rises

Fig.18 Time histories of the double tail vane direction and the rotational speed of the wind turbine ($L_s/L_m = 1.0$, $A_t/A_m = 1.0$, $\theta_l = 90°$, $V = 5 \text{ m/s}$)
constant at about 5.2 rad/s, the $\omega_{p,\text{max}}$ for $A_s/A_m = 1.0$ decreases with an increase in $L_s/L_m$. The maximum angular velocity $\omega_{p,\text{max}}$ depends on the lever length ratio $L_s/L_m$. So, the condition of $L_s/L_m \geq 2.0$ and $A_s/A_m \geq 1.0$ will be appropriate for the overspeed prevention device with double tail vanes.

As shown in Fig. 6, when the wind speed exceeds the margin of safety, the rotational speed is able to be controlled by the sub tail vane with a flap that rises up in strong winds. We examined the relationship between the initial flap angle $\alpha_{\text{flap}}$ and the wind speed $V$ at which the flap rises up. As shown in Fig. 17, the wind speed $V$ at which the flap rises up depends on the initial flap angle $\alpha_{\text{flap}}$ and the board thickness (i.e., mass). The wind speed at which the overspeed prevention device operates can be arbitrarily set by changing the initial flap angle $\alpha_{\text{flap}}$ and the mass of the flap. For example, to provide rotational speed control at wind speeds of 10 m/s or more, the board thickness and the initial flap angle $\alpha_{\text{flap}}$ are set to 1.0 mm (mass: 160 g) and 4°, respectively.

The behavior of the wind turbine with double tail vanes was measured. Figure 18 presents time histories of the rotational speed $N$ of the wind turbine and the angle of the main tail vane (eccentric angle $\theta_p$) under the zero-load condition. The double tail vanes had a lever length ratio of $L_s/L_m = 1.0$, a tail vane area ratio of $A_s/A_m = 2.0$, and an interval angle between the double tail vanes of $\theta_i = 90^\circ$. The sub tail vane was a vertical flat plate, and the wind speed was $V = 5.0$ m/s. The main tail vane immediately turns at $\theta_p = 36^\circ$, and the rotational speed of the turbine decreases with a decrease in the angle of the main tail vane with a phase lag. For 20 seconds, the tail vane vibrates, and the angle of the tail vanes and the rotational speed of the turbine are kept constant at about 47° and 112 min$^{-1}$, respectively. The wind tunnel test confirmed that the rotational speed of the wind turbine can be controlled using double tail vanes.

4.4 Following characteristics of the single tail vane to the wind direction

We examined the following characteristics of the single tail vane, which was installed on the variable-pitch VAWT as shown in Fig. 8, to the wind direction in the field test. Figure 19 shows time histories of the wind speed, wind direction, and angle of the single tail vane (eccentric angle $\theta^*$) for 120 seconds. The directions of the wind and tail vane differ, which are expressed by the incidence angle. However, the motion of the single tail vane follows the wind direction; i.e., the incidence angle remains relatively constant. The frequency distribution of the incidence angle variation at each wind speed in 22.5° increments is shown in Fig. 20. The positive direction is the direction of the wind turbine rotation. For a high wind speed of 7 m/s, the frequency peaks at 0°. For a low wind speed of 2 m/s, the frequency increases at angles greater than +45° or less than −45°. This is because the tail vane drag torque is too small to
overcome the bearing friction in the second shaft. For the self-start and the power of the wind turbine, it is problem that the eccentric angle $\theta_p$ increases. Therefore, the power of wind turbine increases by the decrement of the bearing friction to the tail vane in the second shaft and the increment of the area of a tail vane to steer the tail vane to leeward ($\theta_p = 0^\circ$).

4.5 Validation of the overspeed prevention system

To examine the effectiveness of the overspeed prevention system with double tail vanes, we repeated the field tests with a single tail vane. Figure 21 shows time histories of the wind speed and rotational speed of the turbine for 180 seconds. There are three types of tail vane conditions: main tail vane only, two tail vanes at $\theta_i = 90^\circ$ and $\theta_i = 150^\circ$ with a tail vane area ratio of $A_s/A_m = 1.0$, and two tail vanes with a lever length ratio of $L_s/L_m = 2.0$. The sub tail vane was a vertical flat plate; namely, the flap angle $\alpha_{flap}$ was fixed at $90^\circ$. Each data point corresponding to a mean wind speed of approximately 3.0 m/s was selected. For a single main tail vane (Fig. 21 (a)), the maximum rotational speed of the turbine was about 160 min$^{-1}$. The main tail vane followed the wind direction and maintained position near an eccentric angle $\theta_p$ of $0^\circ$. When the main and sub tail vanes were at an interval angle of $\theta_i = 90^\circ$ (Fig. 21 (b)), the average rotational speed of the turbine decreased to 58 min$^{-1}$, which was smaller than the rotational speed corresponding to the single tail vane case. For an interval angle of $\theta_i = 150^\circ$ (Fig. 21 (c)), although the wind speed was occasionally over 6 m/s, the wind turbine moved very little because the steady-state eccentric angle of the wind turbine with double tail vanes of $\theta_i = 150^\circ$ is $\theta_{p,steady} = 100^\circ$, which is over the angle of the stationary state ($70^\circ$) shown in Fig. 9. Figure 22 shows the frequency distribution of the difference in angle between the wind direction and the double tail vane direction, i.e., the

![Graphs and diagrams showing wind speed and rotational speed variations](image)

Fig.21 Time histories of the wind speed and rotational speed of the wind turbine

![Frequency distribution graph](image)

Fig.22 Frequency distribution of the difference in angle between the wind and the double tail vane ($L_s/L_m=2.0$, $A_s/A_m=1.0$, $\theta_i = 90^\circ$)
steady-state eccentric angle ($\theta_p$, steady = 60°). For a low wind speed of 2 m/s, the frequency increases at angles greater than +45°. For a high wind speed of more than 4 m/s, the frequency peaks at +22.5°. This result means that the performance of the wind turbine with a double tail vane is better than that with a single tail vane because the wind turbine rotational speed peaks at $\theta_p$ = 30°, as shown in Fig. 9.

The characteristics of the wind turbine with the double tail vanes in which the sub tail vane has a flap were measured in field tests. The flap of the sub tail vane has a span of 0.2 m, a width of 0.3 m, a thickness of 0.5 mm, and an initial angle of attack of $\alpha_{\text{flap}}$ = 20° to control the rotational speed for $V \geq 4$ m/s (see Fig. 17). The time histories of the wind speed $V$, rotational speed of the wind turbine $N$, and eccentric angle $\theta_p$ for 60 seconds are shown in Fig. 23. Between 0 sec and 45 sec, the motion of the double tail vane follows the wind direction. When the wind speed is over 4 m/s (from 3 to 5 seconds and from 20 to 23 seconds), the flap of the sub tail vane rises up, and then the eccentric angle $\theta_p$ increases with the wind direction. After 40 sec, the wind speed is less than 2 m/s, and the eccentric angle $\theta_p$ increases because the main tail vane rotates together with the main shaft. The increase in rotational speed is prevented by the double tail vane. It was confirmed in field tests that the proposed overspeed prevention system is able to control the rotational speed of the wind turbine. In practical use, if the generator is installed on the main shaft of wind turbine, the turbine rotational speed with the generator decreases than that without the generator. In consequence, the torque of bearing friction to the tail vane in the second shaft decreases with decreasing the rotational speed, and the gap between the tail vane and the wind direction decreases, i.e., the eccentric angle $\theta_p$ approaches 0 degrees. Thus, the power generation by the variable-pitch vertical-axis wind turbine with the passive controlled tail vanes can harness the wind energy efficiently.

5. Conclusion

The performance of a variable-pitch VAWT with a passive rotational speed control mechanism by means of double tail vanes was investigated in a wind tunnel and in field tests. The effects of the number, size, and location of tail vanes on the performance of the wind turbine were examined. Numerical analyses of the yawing motion of the tail vanes were also performed. The following conclusions can be drawn:

(1) Although the variable-pitch VAWT has directivity to the wind, the power coefficient of the present wind turbine is less sensitive to the yaw angle than that of the propeller wind turbine.
(2) The power coefficient of the present wind turbine with a large and centrally located or lower-located single tail vane is better than with a small and upper-located single tail vane.

(3) There is good agreement in the yawing motion of the double tail vane between the wind tunnel test and the numerical analysis. It is found that the condition of $L_s/L_m \geq 2.0$ and $A_s/A_m \geq 1.0$ is appropriate for the overspeed prevention device with double tail vanes.

(4) The proposed overspeed prevention system can passively control the rotation of the turbine without an electric control system or mechanical brakes and can stop the rotation of the wind turbine in strong winds. We can expect to create a safer small vertical-axis wind turbine using this system.

Acknowledgements

The authors are thankful to technician Mr. Kuratani and students Mr. Tomioka, Mr. Fujine, and Mr. Nagao for their help with the experiment.

Nomenclature

$A_m$ : Area of the main tail vane  
$A_s$ : Area of the sub tail vane  
$C_D$ : Drag coefficient  
$C_L$ : Lift coefficient  
$C_P$ : Wind turbine power coefficient ($= T \omega / \rho R h V^3$)  
$C_{Rm}$ : Restoration coefficient of the main tail vane  
$C_{Rs}$ : Restoration coefficient of the sub tail vane  
$D$ : Turbine diameter  
$I_w$ : Inertia moment of the whole tail vane system  
$L_m$ : Lever length of the main tail vane  
$L_s$ : Lever length of the sub tail vane  
$M_{Rm}$ : Rotational moment from the main tail vane  
$M_{Rs}$ : Rotational moment from the sub tail vane  
$N$ : Turbine rotational speed  
$R$ : Turbine radius  
$T$ : Turbine torque  
$V$ : Wind speed  
$c$ : Blade chord length  
$f$ : Damping coefficient  
$h$ : Turbine height (blade span length)  
$t$ : Time  
$\alpha$ : Geometrical angle of attack  
$\alpha_c$ : Blade offset pitch angle  
$\alpha_{flap}$ : The initial angle of attack of the sub tail vane flap  
$\alpha_m$ : Blade pitch angle amplitude  
$\theta$ : Turbine azimuth angle (angle between main link and eccentric link)  
$\theta_i$ : Interval angle (angle between sub tail vane lever and main tail vane lever)  
$\theta_p$ : Eccentric angle (angle between eccentric link and X-axis)  
$\lambda$ : Tip speed ratio ($= R \omega V$)  
$\rho$ : Air density  
$\phi$ : Blade rotational angle (angle between main link and eccentric link)  
$\phi$ : Yaw angle ($= \phi$)  
$\omega$ : Turbine angular velocity ($= 2 \pi N / 60$)  
$\omega_p$ : Yawing angular velocity of the tail vanes ($= d \phi / dt$)
References

(9) R. Gasch, J. Twele, Wind Power Plants, (2002), Solarpraxis AG.