

Design and Performance Evaluation of Hinge Type Pitch Control System in Small-Size Wind Turbine

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KEYWORDS: Small wind turbine, Hinge mechanism, Pitch control, Kinematic analysis, Jacobian analysis

The present study is about pitch control system of a small wind turbine using hinge mechanism. Small wind turbines generally apply stall control method or breaking equipment over the rated wind speed by reason of price or efficiency. However we perform pitch control applying the hinge mechanism which is simpler than that of medium and large size wind turbines. The hinge mechanism is a kind of linkage. It is composed of a rotation motion part, a linear motion part and a connection part. Pitch angle is controlled by the rotation parts which are connection to blades. In order to determine relationship between the hinge links and pitch angle, kinematic analysis is performed. Also, we derive design specifications of the actuator which drives the hinge mechanism by the Jacobian analysis. Simulation using MATLAB analyses forces and velocities of the hinge type pitch control system. Finally, as applying it to a 20 kW small wind turbine, the performances are evaluated by wind tunnel test.

Manuscript received: September 30, 2015 / Revised: June 17, 2016 / Accepted: June 20, 2016

NOMENCLATURE

A = Area of the rotor

a = Axial induction factor

a_i = Distance from Z_i to Z_{i+1} measured along X_i

c = Cosine

d_i = Distance from X_{i-1} to X_i measured along Z_i

F = Vector of forces at the actuator

F_t = Trust of wind turbine

\dot{m} = Mass flow

s = Sine

v_1 = Wind speed

v_2 = Wind speed in the wake

v_i = Wind speed at rotor plane

β = Pitch angle of wind turbine

δ = Displacement of the actuator

θ_i = Angle from X_{i-1} to X_i measured along Z_i

ρ = Density of air

τ = Vector of torques at the joint

$^iP_{i+1}$ = Vector that locates the origin of the frame $\{i+1\}$

${}_{i+1}^iR$ = Rotation matrix describing frame $\{i+1\}$ relative to frame $\{i\}$

${}^i v_i$ = Linear velocity of the origin of link frame $\{i\}$ with respect to frame $\{i\}$

${}^i \hat{z}_i$ = z direction unit vector frame $\{i\}$ written in terms of frame $\{i\}$

${}^i \omega_i$ = Angular velocity of link frame $\{i\}$ with respect to frame $\{i\}$

1. Introduction

Generation cost of wind power is low against installation charges. However, if it is installed once, it can be used semi-permanently, and it has advantages of pollution-free and high efficiency of land utilization. Especially small wind turbine is under 100 kW wind turbine. It can be used for saving electronic fee at houses, farms and small enterprises. Also it can be used at distant places where it is hard to connect with grid.^{1,2}

Pitch control system of wind turbine keeps blades rotational speed to the designed rotational speed at section of over the rated wind speed. It is used to prevent damages of rotor and blades over the rated wind speed. Its system is comprised of gear or hydraulic system generally.

Since the pitch system equipment is complicated and the installation fee is high,^{3,4} stall control method or breaking equipment is being used instead of that in case of small wind turbines.⁵⁻⁷ Small wind turbines using stall control have their blades designed so that the power production decreases with increasing wind speed over a certain value. The decrease power with increasing wind speed is due to aerodynamic effects on the turbine blades. While the stall control system rely on the aerodynamic design of the blades to control the aerodynamic torque of the turbine in high wind speeds, the pitch control systems use an active pitch control for the blades. This allows the pitch control system to have a constant power output over the rated wind speed, while the stall control systems are not able to keep a constant power output in high winds as Fig. 1. Additionally, since mechanical stress of the stall control is generated higher than that of pitch control, the mechanical load on a turbine structure increases. When applying pitch control method to a small wind turbine, the stability of the turbine structure will be improved and the performance will be far higher over the rated wind speed.

This paper aims to design and evaluate a hinge type system for the pitch control of a small wind turbine. The hinge mechanism is the mechanical equipment which changes rotational motion to linear motion. Chapter 2 introduces the structure of pitch control system applying hinge mechanism. In addition the kinematic and the Jacobian analysis is performed. In chapter 3, the variation of the hinge actuator and pitch angle is examined along wind speed by simulation, and then the proposed hinge mechanism is verified by a wind tunnel test of a 20 kW small wind turbine. Finally, chapter 4 concludes the paper.

2. System Structure and Kinematic Analysis

2.1 Wind Turbine Structure Applying Hinge Type

Fig. 2 shows the whole structure of proposed hinge part in the current study. When a rotating shaft is forced along the shaft, pitch angles of all blades is controlled through the hinge structure. Fig. 3 shows the whole system of wind turbine including hinge set. The shaft penetrates the center of the generator. Though the shaft moves from front to back, it can be rotated by slip rings in the inner generator. A linear actuator is located at the back of the generator and it moves the shaft back and forth. The hinge structure separates into rotational motion part, linear motion part and connection part. A blade joins the rotational part and they move together. Accordingly, when rotational part moves, pitch angle is controlled. The linear actuator connects to the linear part and operates the whole pitch control system.

2.2 Kinematic Analysis of Hinge System Structure

The rotational angle of the hinge joint has nonlinear relationship with actuator displacement. When pitch angle varies, θ_4 rotates together, for they interlocks structurally. Consequently, displacement of the actuator is determined by their relations. Using Fig. 4, sectional plan of the hinge links, relations among β , θ_2 , θ_4 and δ are expressed as follows.

$$\delta = a_0 c \beta + a_2 s (\pi - \theta_4) \quad (1)$$

$$a_0 s \beta + a_4 = a_2 c (\pi - \theta_4) \quad (2)$$

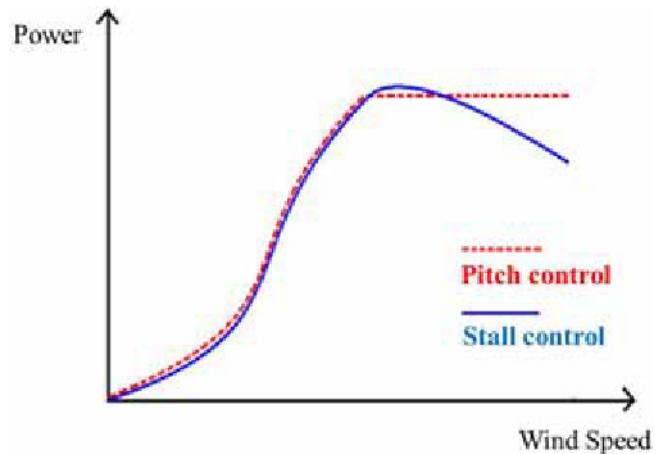


Fig. 1 Power curves of pitch and stall control wind turbines

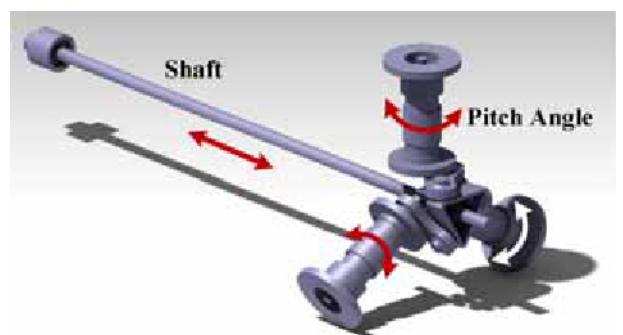


Fig. 2 Structure of hinge type

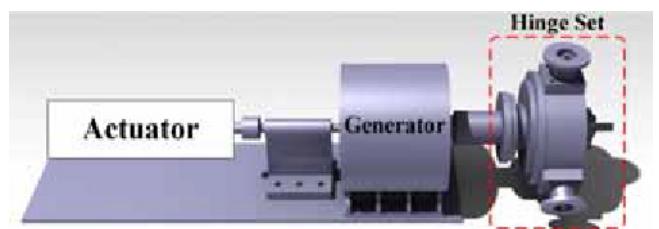


Fig. 3 Structure of the whole wind turbine system

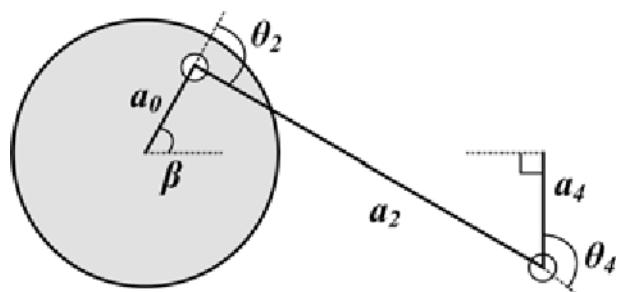


Fig. 4 Sectional plan of the hinge links

$$\beta - \frac{\pi}{2} = \theta_2 - \theta_4 \quad (3)$$

Using the Eqs. (1) and (2), relation of the actuator displacement about pitch angle can be expressed as follows.

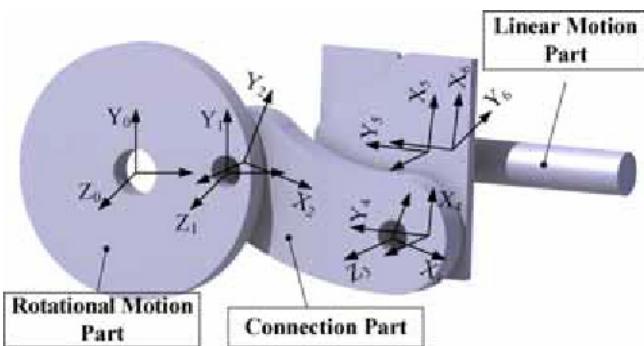


Fig. 5 Frames attached to hinge part

$$\delta = a_0 c \beta + a_2 s \left(c^{-1} \left(\frac{a_0 s \beta + a_4}{a_2} \right) \right) \quad (4)$$

For kinematic analysis, frames from $\{0\}$ to $\{6\}$ are attached to hinge links as Fig. 5. The frame $\{0\}$ rotates along pitch angle and the frame $\{6\}$ is moved by the motion of the actuator attached to the end of linear part. When determining relationship between the frames $\{0\}$ and $\{6\}$, we can know relationship between linear and rotational motion, and force relationship of the actuator about pitch rotational torque.

All Parts of hinge structure are rotational joints. In the frame $\{i+1\}$, angular and linear velocity are expressed as follows.⁸

$${}^{i+1}\omega_{i+1} = {}^{i+1}_i R^i \omega_i + \dot{\theta}_{i+1} {}^{i+1}\hat{Z}_{i+1} \quad (5)$$

$${}^{i+1}v_{i+1} = {}^{i+1}_i R({}^i v_i + {}^i \omega_i \times {}^i P_{i+1}) \quad (6)$$

Then relations of angular and linear velocity about the frames from $\{1\}$ to $\{6\}$ are expressed as follows.

$${}^1\omega_1 = {}^1_0 R^0 \omega_0 + \dot{\theta}_1 {}^1\hat{Z}_1 = {}^0\omega_0 = \dot{\beta} \quad (7)$$

$${}^1v_1 = {}^1_0 R({}^0 v_0 + {}^0\omega_0 \times {}^0 P_1) = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \beta \end{bmatrix} \times \begin{bmatrix} a_0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = a_0 \dot{\beta} \quad (8)$$

$${}^2\omega_2 = {}^2_1 R \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \beta \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \dot{\beta} + \dot{\theta}_2 \quad (9)$$

$${}^2v_2 = {}^2_1 R \begin{bmatrix} 0 \\ a_0 \dot{\beta} \\ 0 \\ \vdots \\ \dot{\beta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ d_2 \end{bmatrix} = \begin{bmatrix} a_0 s \theta_2 \dot{\beta} \\ a_0 c \theta_2 \dot{\beta} \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} a_0 s \theta_2 \dot{\beta} \\ a_0 c \theta_2 \dot{\beta} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (10)$$

$${}^3\omega_3 = {}^3_2 R \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\theta}_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \dot{\beta} + \dot{\theta}_2 \quad (11)$$

$${}^3v_3 = {}^3_2 R \begin{bmatrix} a_0 s \theta_2 \dot{\beta} \\ a_0 c \theta_2 \dot{\beta} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 \end{bmatrix} \times \begin{bmatrix} a_2 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} a_0 s \theta_2 \dot{\beta} \\ (a_0 c \theta_2 \dot{\beta}) \dot{\beta} + a_2 \dot{\theta}_2 \\ 0 \end{bmatrix} = \begin{bmatrix} a_0 s \theta_2 \dot{\beta} \\ a_0 s \theta_2 \dot{\beta} \dot{\beta} + a_2 \dot{\theta}_2 \\ 0 \end{bmatrix} \quad (12)$$

$${}^4\omega_4 = {}^4_3 R \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\theta}_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 + \dot{\theta}_4 \end{bmatrix} \quad (13)$$

$$\begin{aligned} {}^4v_4 &= {}^4_3 R \begin{bmatrix} {}^4\dot{x}_4 \\ {}^4\dot{y}_4 \\ {}^4\dot{z}_4 \end{bmatrix} = {}^4_3 R \begin{bmatrix} a_0 s \theta_2 \dot{\beta} \\ (a_0 c \theta_2 + a_2) \dot{\beta} + a_2 \dot{\theta}_2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ \vdots \\ d_4 \end{bmatrix} \\ &= \begin{bmatrix} \dot{\beta}(a_0 s \theta_2 c \theta_4 + a_0 c \theta_2 s \theta_4 + a_2 s \theta_4) + a_2 s \theta_4 \dot{\theta}_2 \\ \dot{\beta}(-a_0 s \theta_2 s \theta_4 + a_0 c \theta_2 c \theta_4 + a_2 c \theta_4) + a_2 c \theta_4 \dot{\theta}_2 \\ 0 \end{bmatrix} \end{aligned} \quad (14)$$

$${}^5\omega_5 = {}^5_4 R \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 + \dot{\theta}_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\theta}_5 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 + \dot{\theta}_4 \end{bmatrix} \quad (15)$$

$$\begin{aligned} {}^5v_5 &= {}^5_4 R \begin{bmatrix} {}^4v_4 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 + \dot{\theta}_4 \end{bmatrix} \times \begin{bmatrix} a_4 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \\ &= \begin{bmatrix} \dot{\beta}(a_0 s \theta_2 c \theta_4 + a_0 c \theta_2 s \theta_4 + a_2 s \theta_4) + a_2 s \theta_4 \dot{\theta}_2 \\ \dot{\beta}(-a_0 s \theta_2 s \theta_4 + a_0 c \theta_2 c \theta_4 + a_2 c \theta_4) + (a_2 c \theta_4 + a_4) \dot{\theta}_2 + a_4 \dot{\theta}_4 \\ 0 \end{bmatrix} \end{aligned} \quad (16)$$

$${}^6\omega_6 = {}^6_5 R \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 + \dot{\theta}_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \dot{\theta}_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -\dot{\beta} - \dot{\theta}_2 - \dot{\theta}_4 \end{bmatrix} \quad (17)$$

$$\begin{aligned} {}^6v_6 &= {}^6_5 R \begin{bmatrix} {}^5v_5 \\ 0 \\ \vdots \\ \dot{\beta} + \dot{\theta}_2 + \dot{\theta}_4 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ \vdots \\ d_6 \end{bmatrix} \\ &= \begin{bmatrix} \dot{\beta}(a_0 s \theta_2 c \theta_4 + a_0 c \theta_2 s \theta_4 + a_2 s \theta_4) + a_2 s \theta_4 \dot{\theta}_2 \\ 0 \\ \dot{\beta}(-a_0 s \theta_2 s \theta_4 + a_0 c \theta_2 c \theta_4 + a_2 c \theta_4 + a_4) + (a_2 c \theta_4 + a_4) \dot{\theta}_2 + a_4 \dot{\theta}_4 \end{bmatrix} \end{aligned} \quad (18)$$

Since x-direction of the frame $\{4\}$ is fixed, $\dot{\theta}_2$ is expressed as follows using that ${}^4\dot{x}_4$ is 0 from Eq. (14).

$$\begin{aligned} {}^4\dot{x}_4 &= \dot{\beta}(a_0 s \theta_2 c \theta_4 + a_0 c \theta_2 s \theta_4 + a_2 s \theta_4) + a_2 s \theta_4 \dot{\theta}_2 = 0 \\ \therefore \dot{\theta}_2 &= -\frac{\beta}{a_2 s \theta_4} (a_0 s \theta_2 c \theta_4 + a_0 c \theta_2 s \theta_4 + a_2 s \theta_4) \end{aligned} \quad (19)$$

Then ${}^4\dot{y}_4$ is linear velocity of the actuator in Eq. (14), and is derived as an equation about $\dot{\beta}$ using Eq. (19). In other words, using this equation, the relation between pitch angular and the linear velocity of the actuator can be obtained as follows.

$${}^4\dot{y}_4 = \dot{\beta}(-a_0 s \theta_2 s \theta_4 + a_0 c \theta_2 c \theta_4 + a_2 c \theta_4) + a_2 c \theta_4 \dot{\theta}_2 = -a_0 \frac{s \theta_2}{s \theta_4} \dot{\beta} \quad (20)$$

Using Eqs. (2), (3) and (20) can be transformed as Eq. (21) only consisting of variables of pitch angular velocity and linear velocity of the actuator.

$${}^4\dot{y}_4 = -a_0 \frac{s\left(\beta + \frac{\pi}{2} - c^{-1}\left(\frac{a_0 s \beta + a_4}{a_2}\right)\right)}{s\left(\pi - c^{-1}\left(\frac{a_0 s \beta + a_4}{a_2}\right)\right)} \dot{\beta} \quad (21)$$

In Eq. (20), when one of θ_2 and θ_4 becomes 0° or 180° , hinge links has singularity. Accordingly, it has to be operated as avoiding this area. The theta-4 doesn't become 0° or 180° by the feature of the hinge links. However, θ_2 is all able to become both 0° and 180° . Consequently, the hinge links has to avoid this area. As the range of pitch angle is generally about 95° , we can set the working section that the hinge links is operated by avoiding singularity area.

2.3 Jacobian Analysis of Hinge Actuator

Velocity relationship between joints and orthogonal coordinates is called the Jacobian. In addition, ${}^6J(\Theta)$, the Jacobian about relationship between rotational velocity of links and linear velocity of the actuator, is expressed using Eq. (18) as follows.

$$\begin{aligned} {}^6v &= {}^6J(\Theta)[\dot{\beta} \ \dot{\theta}_2 \ \dot{\theta}_4]^T = {}^6J(\Theta)\dot{\Theta} \\ {}^6J(\Theta) &= \begin{bmatrix} a_0 s \theta_2 c \theta_4 + a_0 c \theta_2 s \theta_4 & a_2 s \theta_4 & 0 \\ 0 & 0 & 0 \\ -a_0 s \theta_2 s \theta_4 + a_0 c \theta_2 c \theta_4 + a_2 c \theta_4 + a_4 & a_2 c \theta_4 + a_4 & a_4 \end{bmatrix} \end{aligned} \quad (22)$$

Also, in force domain, the Jacobian can be expressed as follows.

$$\tau = {}^6J(\Theta)^T F \quad (23)$$

where $\tau = [\tau_1 \ \tau_2 \ \tau_3]^T$, $F = [F_x \ F_y \ F_z]^T$.

When the equation is expressed only about, τ_1 , pitch rotational torque of blade, Eq. (23) can be transformed as Eq. (24) for short. In this equation, since x and y-direction of the frame {6} are fixed, terms of F_x and F_y disappear, and term of F_z , force of the actuator, only appears.

$$\tau_1 = (-a_0 s \theta_2 s \theta_4 + a_0 c \theta_2 c \theta_4 + a_2 c \theta_4 + a_4) F_z \quad (24)$$

We use the following formula to find force of the actuator required by wind loading. In addition, F_T , thrust of wind turbine by wind power is derived as follows.^{9,10}

$$F_T = \dot{m}(v_1 - v_2) \quad (25)$$

Also, Eq. (25) can be transformed as Eq. (26) using the next formula.

$$F_T = \rho A v_i (v_1 - v_2) = \rho A \frac{v_1 + v_2}{2} v_i \left(1 - \frac{v_2}{v_1}\right) \quad (26)$$

In addition, a is defined as follows.¹¹

$$a = \frac{v_1 - v_t}{v_1} \quad (27)$$

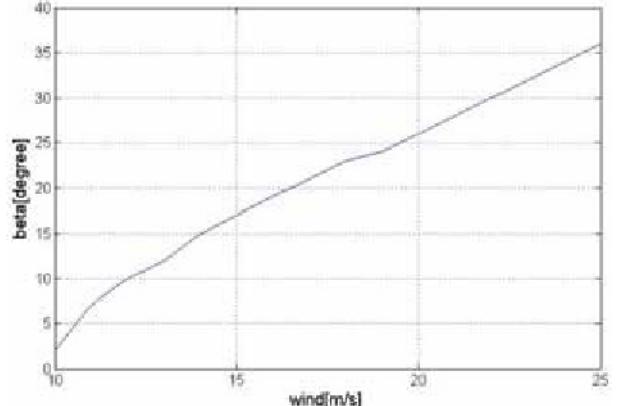


Fig. 6 Pitch angle variation by wind speed

This equation can be transformed about v_2 .

$$\begin{aligned} v_1 a - v_1 &= -v_t = -\frac{v_1 + v_2}{2} \\ \therefore v_2 &= v_1 - 2v_1 a \end{aligned} \quad (28)$$

By substituting Eqs. (28) in (26), we can obtain a following equation.

$$F_T = \rho A \frac{v_1 + v_1 - 2v_1 a}{2} v_i \left(1 - \frac{v_1 - 2v_1 a}{v_1}\right) = 2\rho A v_1^2 a (1-a) \quad (29)$$

In addition, force of the actuator about wind speed is can be derived as Eq. (30) using Eqs. (3), (24) and (29) by the formula of trigonometric functions.

$$\begin{aligned} F_z &= \frac{2\rho A v_1^2 a (1-a)}{a(c \theta_2 c \theta_4 - s \theta_2 s \theta_4) + a_2 c \theta_4 + a_4} \\ &= \frac{2\rho A v_1^2 a (1-a)}{a_0 c \left(\beta - \frac{\pi}{2} + 2\theta_4\right) + a_2 c \theta_4 + a_4} \end{aligned} \quad (30)$$

3. Simulation and Experiment

Before a test, we simulate the pitch actuator applying the hinge mechanism using MATLAB software. When pitch angle varies over the rated wind speed, the force, the velocity and the displacement of the actuator are analyzed by the hinge mechanism. First, in order to know the force of the actuator by wind speed, we check pitch angle variation for the rated power over the rated wind speed as Fig. 6. In other words, when pitch angle is controlled as Fig. 6 along wind speed, the wind turbine can generate the rated power. Accordingly, the force on the actuator varies nonlinearly. Fig. 7 shows the variation of the force on the actuator when pitch angle varies along wind speed for the rated power.

The range of pitch angular velocity is generally limited to the bounds of $\pm 7^\circ/\text{s}$.¹² Within the boundaries, velocity variation of the actuator about each pitch angle is shown as Fig. 8. We can check that the actuator velocity varies at all the pitch angle area by the feature of the hinge mechanism. Especially its velocity is the highest at around 60° . As using the actuator velocity and variation of force, Figs. 7 and 8, design specifications of the actuator applying hinge mechanism can be determined.

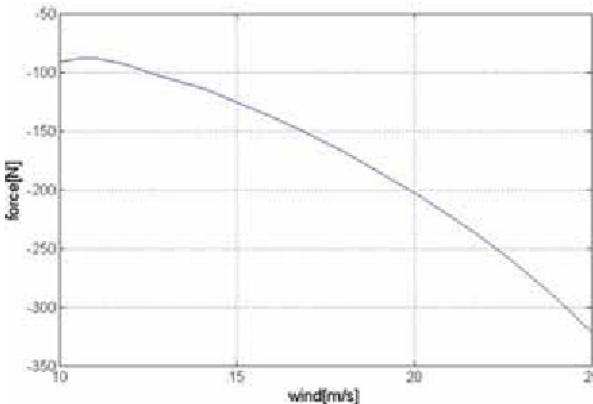


Fig. 7 Force working on the actuator

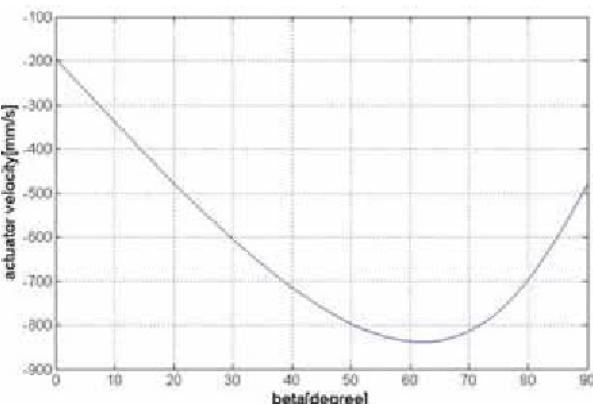


Fig. 8 Actuator velocity by pitch angle

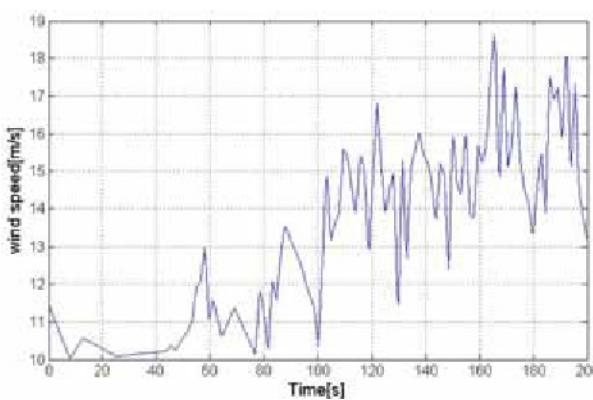


Fig. 9 Kaimal wind speed model used in simulation

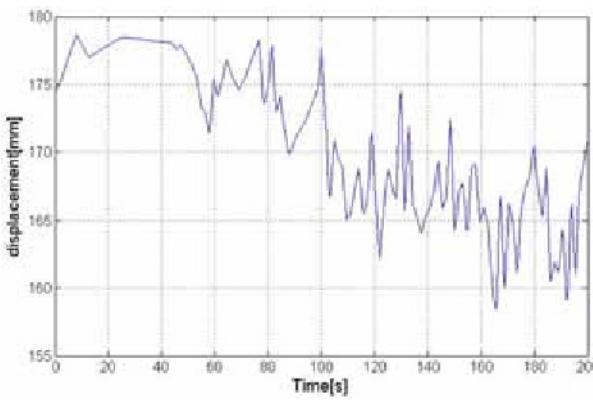


Fig. 10 Delta variation for rated power

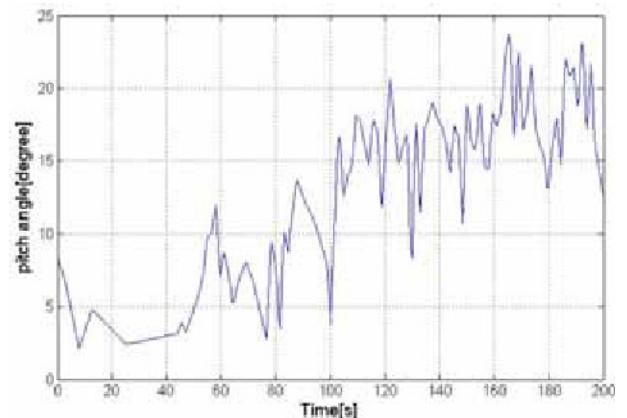


Fig. 11 Beta variation by delta

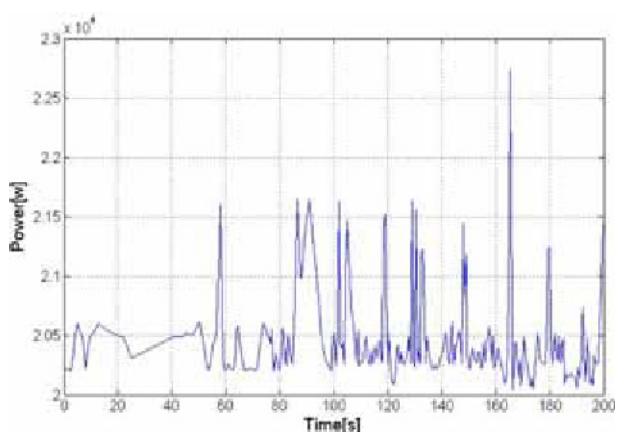


Fig. 12 Generator power over rated wind speed

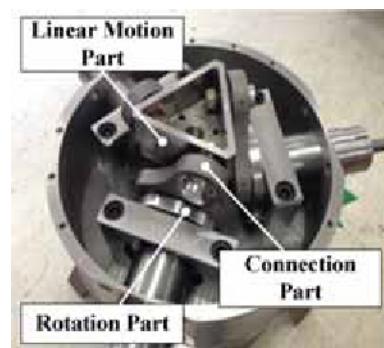


Fig. 13 Manufactured pitch actuating system using hinge type

We check the variations of the hinge links and the actuator about real wind speed model. About Kaimal wind speed model as Fig. 9,¹³ when the actuator is operated as Fig. 10, pitch angle is controlled as Fig. 11. Consequently, the wind turbine can generate the rated power in spite of variation of wind speed. Fig. 12 shows that the rated power is kept around 20 kW. Since pitch angle is controlled by open-loop at intervals of 1°, there is a little deviation in the power at the range from 20 to 23 kW.

We manufactured the pitch control system applying hinge type designed as Fig. 13 and applied it to a 20 kW small wind turbine. Since it works in the ranges of 93°, it can avoid the singularities. The actuator

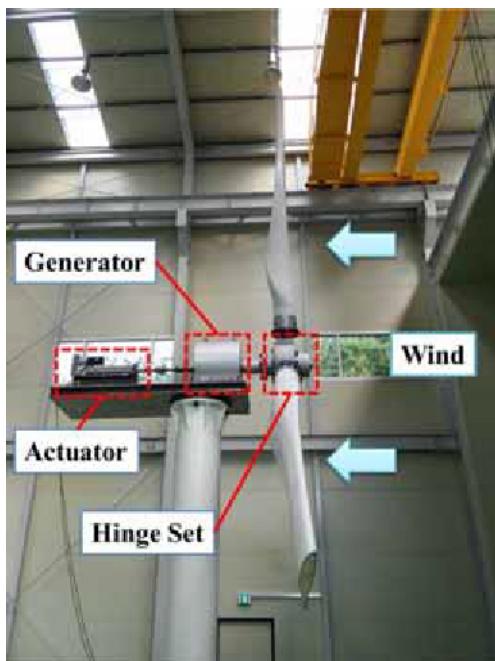


Fig. 14 Manufactured small wind turbine system using hinge type

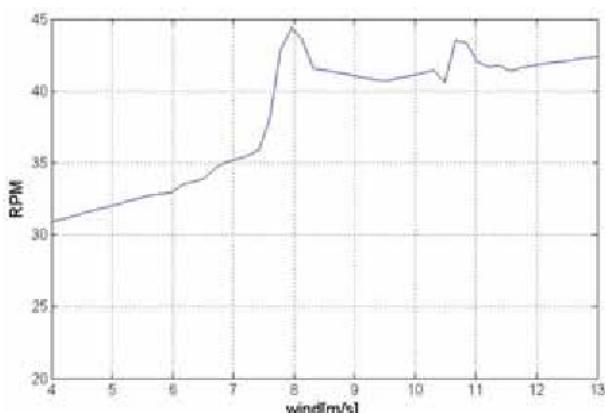


Fig. 15 RPM variation on wind turbine performance testing

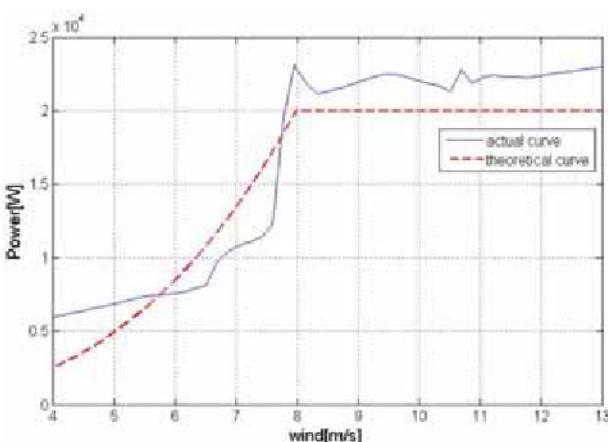


Fig. 16 Generator power on wind turbine performance testing

is selected by the features of Figs. 7 and 8. Also, we installed the wind turbine including it in a wind tunnel as Fig. 14, performed tests and

observed the results. The tests are how well the pitch control system applying it operates over the rated wind speed and how well the wind turbine generates the rated power.

Figs. 15 and 16 show test results in the wind tunnel. The wind turbine starts operation at 4 m/s wind speed. Since the wind turbine starts to generate the rated power at 8 m/s, the pitch control system starts operation at that wind speed. As wind speed increases over the rated wind speed, power coefficient falls by controlling pitch angle, and rotational velocity of the wind turbine can be controlled. In Fig. 15, we can check that rotational velocity is controlled to the range from 40 to 44 rpm over the rated wind speed. Fig. 16 shows that actual curve follows theoretical one generally. Before 8 m/s, the generator power is increased along wind speed, and after 8 m/s, the generator power is kept around the rated power, 20 kW. In the region over the rated wind speed, 8 m/s, the actual curve is above theoretical one. In the same with simulation result in Fig. 12, we can check that the generator power is maintained at the range from 20 to 23 kW above the rated power.

4. Conclusions

In conclusion, a hinge type pitch control system which can be applied to small wind turbines was proposed. While stall control system which is used in small wind turbines decreases power in high wind speed, pitch control system can maintain the rated power above the rated wind speed. Since the hinge mechanism is a kind of linkage, it has to be operated only in the continuous range of avoiding singularity area. This range was designed to be wider than that of pitch angle from kinematic analysis. The specifications of the actuator working against wind loading were derived from the Jacobian analysis. Simulation and experiment results show that the hinge pitch control system can be operated above the rated wind speed and a 20 kW small wind turbine can generate more than the rated power. Robust control method of the proposed system is one of future works.

ACKNOWLEDGEMENT

This work was supported by the Human Resources Development program (No. 20134030200290) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy.

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APPENDIX

The model parameters used in the test are shown in Table 1.

Table 1 Parameters setting

A (m ²)	80.118
ρ (kg/m ³)	1.21
a_0 (m)	0.0685
a_2 (m)	0.12
a_4 (m)	0.045

Transformation matrixes between the frames are as follows.

$${}_0^1R = {}_2^3R = {}_4^5R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad {}_1^2R = \begin{bmatrix} c\theta_2 & s\theta_2 & 0 \\ -s\theta_2 & c\theta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$${}_3^4R = \begin{bmatrix} c\theta_4 & s\theta_4 & 0 \\ -s\theta_4 & c\theta_4 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad {}_5^6R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}$$