Study on cyclic pitch control of HAWT by using instantaneous inflow observation

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Abstract. The power output of a wind turbine depends on both wind speed and turbine control. There is a fluctuation in the natural wind speed, which changes the turbine power output. In this paper blade pitch control based on detailed monitoring of the inflow wind, including vertical velocity distributions, has been experimentally evaluated in a field test wind turbine. The inflow wind speeds were observed by 11 sets of ultrasonic anemometers. In this first test, the blade pitch is changed to keep optimum angle of attack based on the local inflow wind speed in the rotor plane. The blade pitch is independently controlled as a reference radial position of 80% of rotor radius. As a result of the pitch controls, the wind turbine power output was increased and the power output fluctuation was decreased for the cyclic pitch control based on the local wind speed. With the cyclic pitch control, the fluctuation in rotor thrust and average rotor thrust were also reduced compare to collective pitch control.

1. Introduction

The power output of a wind turbine depends on both wind speed and turbine control. There is a fluctuation in the natural wind speed, which changes the turbine output. The power output fluctuations affect electrical grid stability. In addition, the power output fluctuations also cause blade load fluctuations. The load fluctuations increase the risk of fatigue of wind turbine components. The inflow observation system is currently in practical use. The Lidar system has the good potential for wind turbine applications. Potential advantages include increased energy output and reduced fatigue damage [1]. There are many studies related to feed forward control with preview wind. Dunne et al. [2] have studied combined feedback/feedforward control with coming wind speed measurement. D Schlipf et al. [3] have studied the correlation of the rotor effective wind speed between a Lidar system and a wind turbine with field test data. The multipoint Lidar system is useful to observe the inflow distribution [4].

In this paper a blade pitch control based on the detail monitoring of inflow wind, which includes vertical speed distributions, is experimentally evaluated on a field test wind turbine. Two types blade pitch controls, which based on hub height inflow speed (collective pitch) and vertical wind speed distribution (cyclic pitch), are tested for the first trial. The blade pitch is changed based on the local wind speed of the rotor plane. The blade pitch is independently controlled as a reference position of 80% of radius. As a result of pitch control, in the case of independent pitch control by local wind speed, the wind turbine output is increased and the power output fluctuation is decreased. With the cyclic pitch control, the fluctuation in the rotor thrust and averaged rotor thrust were also reduced compare to the collective pitch control.
2. Objectives
In this study, the feedforward control based on the wind speed upstream of the wind turbine is studied in order to suppress the power output fluctuation under natural wind. Preliminary tests are performed using field test facility. Considering the vertical distribution of wind speed from the upstream wind observation mast, the cyclic pitch control that controls the pitch angle independently for each azimuth angle is introduced to reduce the power output fluctuation and the blade load fluctuation. The collective pitch control by the observation of the inflow wind at the hub height is compared with the cyclic pitch control, and the effect is verified.

3. Experimental setup and methods

3.1. Test wind turbine
Figure 1 shows a test HAWT with an individual pitch system. The test wind turbine has a rotor diameter of 10.0 m, a hub height of 13.4 m, and a three-blade upwind rotor. The generator capacity is 37 kW. The pitch angle of each blade is controlled by a servo motor with the pitching speed of 7.4 degree/sec. The three set of servo controllers and a programmable controller with wi-fi communication are set in the hub. When the pitch angle is cyclically changed as the SIN function with the rotor speed of 50 rpm, the pitch angle amplitude during one rotation of the rotor can be set to a maximum of 8.8 degree. The rotor blade is twisted taper blade made of FRP. To measure the rotor thrust, the nacelle is connected to the tower via a set of linear motion guide. The nacelle can move a little in the axial direction and a high-precision tensile load cell was set between tower side and nacelle side. The resolution of the load cell used for thrust measurement is 0.12 N, and the measurement accuracy is ±10 N when the thrust is 20 kN.

![Figure 1. Test wind turbine](image)

3.2. Inflow observation system
Figure 2 shows the inflow observation system. The reference masts are installed at 10.0 m upstream from the rotor. The inflow wind distribution is observed with 11 sets of ultrasonic anemometers, a cup anemometer, and a vane. 7 sets of ultrasonic anemometers measure horizontal distribution of inflow at hub height. The others measure the vertical distribution at top and bottom heights of the rotor. The ultrasonic anemometer measures the three-dimensional wind velocity at a sampling frequency of 50 Hz. All recorded data is sent to the main controller PC via a fiberoptics network. Since the main wind direction of this test site is 303°, the seasonal wind becomes strong in winter season. So, the test in
winter season, this observation system can detect detail velocity profile of the inflow wind. The experiments are limited to a wind direction of 303°.

3.3. Cyclic Pitch control
In this study the simple method to set pitch angle are tested. The pitch control set the pitch angle order to maintain the optimum angle of attack at r/R=0.8 for each azimuth angle of blades. The optimum angle of attack was calculated by the optimum tip speed ratio \( \lambda_{opt} \) and the optimum pitch angle, \( \beta_{opt} \). The pitch angle can be set in the range of \( 2^\circ < \beta < 70^\circ \). The optimal angle of attack \( \alpha_{opt} \) is

\[
\alpha_{opt} = \frac{180}{\pi} \arctan \left( \frac{1}{\lambda_{opt}} \right) - \beta_{opt}
\]

The pitch angle \( \beta \) for \( \alpha_{opt} \) in case of measured \( \lambda \) is

\[
\beta = \frac{180}{\pi} \arctan \left( \frac{1}{\lambda} \right) - \alpha_{opt}
\]

From the past research, the optimal tip speed ratio for this blade is \( \lambda_{opt} = 6 \) and the optimal pitch angle is \( \beta_{opt} = 2^\circ \). The pitch angle was controlled according to the azimuth position of the blade. The pitch angle order is issued independently for each blades. The optimum pitch angle was selected using the equations (1) and (2) based on the average wind speed over one second. The pitch angle order for cyclic pitch control is set to maintain the optimum angle of attack at azimuth angles of 0 \( ^\circ \) and 180 \( ^\circ \), which indicate the maximum and minimum wind speed due to the wind shear. In this study, in order to eliminate the time delay of the pitch control, the arrival time of the measured inflow wind on the rotor is predicted. The time \( \Delta t \) [s] from the inflow wind passing through the anemometer of the inflow wind observation mast to reaching the rotor is expressed by the following equation.

\[
\Delta t = \frac{L}{U}
\]

Here, \( L \) [m] is the distance from the inflow wind observation mast to the wind turbine rotor (\( L = 10.0 \) [m]). The pitch angle order with the corrected time was scheduled. The pitch angles were changed on
the pitch schedule. In addition, on the wind speed increase case the wind arrives faster than previously observed wind, the pitch schedule is updated. The pitch order interval for the cyclic control is twice per one rotation of the blade, so total amount of pitch order per one rotation of the rotor is 6 times. For the collective pitch control, the pitch angle order for each blade is the same and the pitch angle is changed simultaneously for three blades at same scheduled timing. The pitch order interval for the collective control is once per one rotation of the rotor.

4. Results and discussion

4.1 Inflow wind speed distribution

The vertical profile of wind speed was determined using the inflow wind observation system. Figure 3(a) shows the example of the vertical wind profile and relation between the height \( h [\text{m}] \) and wind speed \( U [\text{m/s}] \). The data shown in figure are measured with ultrasonic anemometers for the wind direction of \( 303 \pm 5^\circ \). From figure 3(a), the wind speed increases with height. The vertical profile was generally expressed by a power law approximation. The exponent was 0.263 based on the measured data.

\[
U(z) = U_0 \left( \frac{z}{z_0} \right)^{0.263} \tag{1}
\]

The wind speed increase as a nearly linear function in the rotor height, the reference wind speed for control is estimated by linear interpolation based on the instantaneous observation results.

The horizontal distribution of wind speed was determined. The results are shown in figure 3(b). In figure, the horizontal axis shows the dimensionless measurement position with respect to the rotor radius, and the vertical axis shows the wind speed \( U [\text{m/s}] \). In this test site, the left side \( (y/r<0) \) shows the forest direction and the right side \( (y/r>0) \) shows the field direction. There is a tendency that the wind speed is higher on the field side and lower on the forest side. Also, the change in wind speed tends to become smaller as it approaches the field side. The wind speed change in \( y \) direction is ignored in the pitch order calculation.

![Velocity profile of inflow wind at test site.](image)

\(4.2\) Evaluation of cyclic pitch control by using instantaneous inflow observation

The test rotation speed of the wind turbine was fixed at a fixed rotation speed \( N = 50 \ [\text{rpm}] \) to find the effect of the proposal pitch control. In order to verify the performance of the cyclic pitch control, we compared the time series data of power output and rotor thrust of the cyclic pitch control and the collective pitch control. The data extraction conditions were as follows: for both controls, the nacelle direction was \( 303^\circ \), the wind direction was \( 303\pm5^\circ \), the average wind speed was 5.0 m/s and the standard deviation of the wind speed was 1.4 m/s for 2 minutes.
4.2.1 Effect on power output fluctuation
Figure 4 shows the wind speed and the power output under the cyclic pitch control. The figure shows the time $t$ [s] on horizontal axis, the wind speed $U$ [m/s] on first vertical axis, and the power output $P$ [kW] on second vertical axis. The black line indicates $U$ and the red line indicates $P$. Figure 5 shows the wind speed and the power output under the collective pitch control. The horizontal and vertical axes in the figure are the same as in figure 4. In case of the cyclic pitch control, the average power output for two minutes was 1.61 kW, the standard deviation of the power output was 1.22 kW, and the variation in the power output per 1 kW was 0.756. In case of the collective pitch control, the average power output was 1.58 kW, the standard deviation of the power output was 1.28 kW, and the variation in the power output per 1 kW was 0.810.

![Figure 4. Wind speed and power output under the cyclic pitch control](image1)

![Figure 5. Wind speed and power output under the collective pitch control.](image2)
From the discussion above, as shown in figure 6, with the same average wind speed and the same wind speed standard deviation, the cyclic pitch control increases the power output about 1.02 times compared with the collective pitch control. In addition, the power output fluctuation per 1kW is reduced about 0.93 times. It can be said that the cyclic pitch control was effective even when compared with the collective pitch control. This is because, under the collective pitch control, the operating tip speed ratio for the local blade section decreases when the local blade section receives high wind speed near top of rotor swept area, the power output decreases. On the other hand, the cyclic pitch control can maintain the optimum angle of attack in spite of the wind speed variation with azimuth by the wind shear.

4.2.2 Effect on load fluctuation
Figure 7 shows the wind speed and the rotor thrust under the cyclic pitch control. The figure shows the time \( t \) [s] on the horizontal axis, the wind speed \( U \) [m/s] on the first vertical axis, and the rotor thrust \( T \) [N] on the second vertical axis. The black line represents the wind speed \( U \), and the red line represents the rotor thrust \( T \). Figure 8 shows the wind speed and the rotor thrust under the collective pitch control. The horizontal and vertical axes in the figure are the same as in figure 7. In the cyclic pitch control, the averaged rotor thrust for 2 minutes was 152 N, the standard deviation of the rotor thrust was 133 N, and the variation in the rotor thrust per 1N was 0.858. The averaged rotor thrust under the collective pitch control was 175 N, the standard deviation of the rotor thrust was 157 N, and the variation in the rotor thrust per 1N was 0.897.

From the data above, as shown in figure 9, with the same average wind speed and the same wind speed standard deviation, the rotor thrust is reduced about 0.87 times in the cyclic pitch control compared to the collective pitch control. Also, the variation of the rotor thrust per 1N is about 0.96 times, and it can be said that the cyclic pitch control was effective even when compared with the collective pitch control.
Figure 7. Wind speed and rotor thrust under the cyclic pitch control.

Figure 8. Wind speed and rotor thrust under the collective pitch control.
Figure 9. Comparison of rotor thrust under cyclic and collective pitch controls

5. Conclusion

In this study, the feedforward control based on the wind speed upstream of the rotor is studied. The preliminary tests are performed with field test facility. The power output fluctuations of the cyclic pitch control and the collective pitch control with inflow wind observation were compared.

The fluctuation amplitude on the power output of the cyclic pitch control was smaller than that of the collective pitch control. In addition, the power output under the cyclic pitch control was increased compared to the collective pitch control.

The fluctuation amplitude on the rotor thrust of the cyclic pitch control was smaller than that of the collective pitch control. In addition, the rotor thrust under cyclic pitch control was reduced compared to the collective pitch control.

In the cyclic pitch control, the possibility of suppressing the output and rotor thrust fluctuation was shown.

6. References

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