Enhanced Yaw Stability of Downwind Turbines

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Abstract. It is shown, in a novel experimental study using a sub-scale model of a 5MW downwind turbine, that individual pitch control based on a sinusoidal pitching scheme that is locked to the phase of the rotor rotation further improves the yaw stability of a downwind turbine. The optimum pitching amplitude is observed to be insensitive to yaw angle. Furthermore, a positive pitching amplitude improves yaw stability at negative yaw angles, while at positive yaw angles, negative pitching amplitude improves yaw stability. Thus, individual pitch control further improves the superior yaw characteristics of downwind turbines compared to upwind configurations.

1. Introduction
As the size of wind turbines becomes increasingly larger, downwind turbines, which have less constraints than upwind turbines as regards tower to blade tip clearance [1-2], allow for lighter and more slender rotor blade designs. On downwind turbines, rotor tilt and blade cone can reduce the impact of the tower wake and also allow for an increased blade length because of higher allowable deflection [3]. However, rotor tilt causes a periodic variation in the velocity seen by each blade [4] since each blade section translates into/out of the wind during a revolution of the rotor. From a mechanical perspective, rotor tilt also causes a component of the turbine torque to be transmitted into the tower since the tower is no longer perpendicular to the drive train. Transmission of a torque component into the tower can reduce yaw stability [5-7], promoting further divergence of the rotor away from the zero yaw position; consequently, rotor tilt is absent in “free-yawing” wind turbine designs [8]. Notwithstanding the above, downwind rotors have improved yaw stability compared to upwind rotors [9, 10].

Simulations have shown that individual blade pitch control is a possible approach for load reduction on wind turbines [11-13]. On upwind turbines, individual pitch control has been examined as a means to mitigate the unsteady loads caused by wind shear, blade-tower-interaction, yaw/tilt, and turbulence as well as gravitational loads acting on the blades [14]. Recently, closed-loop control of the blade lift has been considered to dynamically alleviate the mechanical loads due to wind gusts. Some of these approaches are based on the feedback from the tower and the blade loads. These approaches either target the combined or the separate design of the individual pitch control and/or the collective pitch control [15-20].

The present work is novel in that experimental studies of individual pitch control on downwind turbines are conducted. An individual pitch control algorithm to compensate for the effects of rotor tilt (and/or yaw) at design tip speed ratio (λ) with and without yaw is developed and tested. A detailed explanation of the effectiveness of the compensation and a suggested strategy for IPC to enhance further the yaw stability of downwind turbines are presented.
2. Methodology

The experimental study has been conducted with a 1/210 scale model of the Hitachi HTW5.0-127 wind turbine (Figure 1). The turbine model has a rotor diameter D of 0.6 m, a rotor tilt of 8°, and a cone angle of 5°. Geometrical scaling is used [18], and all lengths are scaled down similarly but the root of the blade is modified to install the IPC motor and to manage loads at the blade root. The new design has been verified from BEM simulation to match the $C_t$ and $C_p$ of the original turbine. The tip speed ratio of the model turbine is the same as that of the full-scale turbine. The wind turbine test facility (WEST) at ETH Zürich, Figure 2, a 40 m long, 1m wide and 1m deep water tank over which a carriage is towed, is used to test the model. Water towing tanks used for experiments on scaled models of marine vessels [22], for testing models of marine current turbines [23], tidal [24] [25] and wind turbines [26]. The water tank is an open section flow channel and the model has a solidity ratio of 7% relative to the tank’s cross-section, thus a blockage correction factor is applied. The model is mounted upside-down on a carriage that traverses the channel, allowing the model to be moved through the water. The freestream turbulence intensity of 8% is generated by injecting cross-flow jets through perforations in streamlined aerofoils shown as the turbulence generator in Figure 2. To eliminate the effect of surface wave, for each test, the water channel is re-filled to compensate for splashed water. The turbine rotational speed N at design tip speed ratio ($\lambda_{design}$) is 354 rpm. The Reynolds number based on the blade chord length at 75% span at design tip speed ratio varies over the range $8.0 \times 10^4$ – $9.0 \times 10^4$, depending on the operating point. Thus, as on the full-scale wind turbine the Reynolds numbers are typically between $5.0 \times 10^6$ and $1.0 \times 10^7$, the measurements are corrected for Reynolds number effects.

![Figure 1. Photograph of HTW5.0-127 wind turbine [24].](image1)

![Figure 2. View from above of the wind turbine test facility (WEST) facility at ETH Zürich.](image2)

The tip speed ratio ($\lambda$) is controlled by specifying the carriage velocity and turbine speed. During measurement, the shaft torque, turbine thrust, tower bending and twist moments are sampled at 10 kHz. The rotor torque is measured using a custom-built torque shaft that is instrumented with strain gauges and telemetry. The electric motor of the powertrain functions as a generator, and the power (P) produced by the turbine is determined from the measured driveshaft torque and turbine speed; the power coefficient ($C_P$) is calculated as:

$$C_P = \frac{P}{\frac{1}{2} \rho AV^3}$$

(1)

where A is the cross-sectional area of the rotor and V is the inflow velocity of the turbine.
A strain gauge configuration at the root of the tower of the turbine is used to measure the bending and twisting moments. The thrust coefficient ($C_T$) and the moment coefficient ($C_M$) are given as:

$$C_T = \frac{T}{\frac{1}{2} \rho A V^2}$$

(2)

$$C_M = \frac{M}{\frac{1}{2} \rho V^2 C_{75\%} A_{blade}}$$

(3)

where the thrust on the rotor ($T$) is the difference of the measured thrusts with and without the blades installed. The moment coefficient ($C_M$) is evaluated using the twisting moment acting on the tower ($M$) measured with the blades installed, the chord-length at 75% span ($C_{75\%}$) and the blade suction-side surface area ($A_{blade}$). Table 1 summarises the measurement uncertainties.

**Table 1.** Uncertainties (due to sensor characteristics) in measured quantities for reference case of zero yaw and $\lambda_{opt}$.

| Quantity                      | Standard uncertainty (sensor characteristics) |
|-------------------------------|-----------------------------------------------|
| Rotor torque                  | ±0.8%                                         |
| Power coefficient $C_P$       | ±1.9%                                         |
| Thrust coefficient $C_T$      | ±2.0%                                         |
| Yaw moment coefficient $C_M$  | ±7.0%                                         |

A custom-built signal transmission system transmits power and control signals from a nacelle-mounted stator antenna to a hub-mounted rotor antenna (Figure 3). Pitch motors installed in the blade root and controlled by control systems contained within the rotor hub are used to independently position the blades.

Figure 3. Oblique view of the model wind turbine; the model is based on the Hitachi HTW5.0-127.

Figure 4a shows the velocity triangle for a section of the blade, where $V$ is the incoming flow velocity, $U$ is the blade velocity, and $V_{rel}$ is the blade relative flow velocity. The induced velocity $w$ is parallel to the lift force $L$. As a turbine has rotor tilt (Figure 5), advancement/retreat of the blade into/out of the wind causes a variation in the induced velocity ($w$) at each blade section. The induced velocity is larger, when the blade points downstream than half a revolution later when the same blade points upstream. This means that a blade pointing downstream is deeper into the wake than a blade that is pointing upstream. On the other hand, the upstream blade (Figure 4c) sees a higher wind speeds and thus produces higher loads than the downstream blade (Figure 4b) [25].
Figure 4. Velocity triangles at a blade section when the blade is in intermediate, top-most and bottom-most positions.

Figure 5. A clockwise-rotating downwind turbine with rotor tilt showing axial displacement of the blade tip.
As the turbine has rotor tilt, advancement/retreat of the blade into/out of the wind causes a variation in the relative velocity at each blade section. A corrective pitch adjustment that is added to the collective pitch angle is used in this work to compensate for the velocity variation that is induced by the rotor tilt. The corrective pitch adjustment is linearly related to the rate of advancement/retreat,

\[ P_{pc} = D \sin \theta \]  

(4)

where \( D \) is a proportionality constant, and \( \theta \) is the azimuthal position of the rotor. Table 2 summarises the test matrix.

| Parameter         | Range                        |
|-------------------|------------------------------|
| Orientation       | Downwind                     |
| Tilt angle        | 8°                           |
| Cone angle        | 5°                           |
| Yaw angle         | 0°, ±4°, ±8°, ±16°           |
| Tip speed ratio   | \( \lambda_{design} \)       |
| Pitching scheme   | Sinusoidal                   |
| Pitch amplitude   | 0°, ±0.8°, ±1.6°, ±2.4°, ±3.2°|

3. Results

Figure 6 compares the effect of individual pitch control (IPC) on power for the cases without and with ±16° yaw. In Figure 6 the power coefficient is normalised by the power coefficient for no yaw and no IPC (\( \text{C}_{p00} \)). It can be seen that with a pitching amplitude of -1.6° for all yaw angles, peak power is achieved, indicating that the optimum pitching amplitude is independent of yaw. For non-positive pitching with amplitudes less than the optimum pitching amplitude, IPC increases power output. Figure 7 shows that the trends in thrust follow the trends in the output power. It can be seen that with a sinusoidal pitching amplitude of -1.6° for all yaw angles, peak thrust is achieved.

![Figure 6](image1.png)

**Figure 6.** Effect of individual pitch control (sinusoidal scheme) on power for yaw angles of 0° and ±16°.

![Figure 7](image2.png)

**Figure 7.** Effect of individual pitch control (sinusoidal scheme) on thrust for yaw angles of 0° and ±16°.

The effect of IPC on the yawing moment, with no IPC and pitching amplitudes of ±1.6°, is shown in Figure 8. The corresponding yaw stability coefficient, which is the differences of the coefficients of
the moment with and without yaw (\(C_M - C_{M0}\)) normalised by the coefficient of the moment without yaw and no IPC (\(C_{M0}\)), is shown in Figure 9. A zero or positive slope indicates neutral stability or yaw instability, respectively while a negative slope is indicative of the turbine’s yaw stability. Over yaw angles in the range -8° to +16°, for the case of no IPC, the slope is constant; over the range -16° to -8° the magnitude of the slope is reduced, indicating a reduced yaw stability of the downwind turbine. This means that the yaw stability with a positive rotor yaw angle is more than with a negative yaw angle. On the other hand, the turbine is more stable when it has a positive yaw angle in comparison to when the turbine has a negative yaw angle. A positive pitching amplitude of +1.6°, increases the magnitude of the slope compared to the case without IPC over the yaw angles in the range of -16° to -8°; conversely, a negative pitching amplitude of -1.6° decreases the magnitude of the slope compared to the case without IPC. It is evident that at negative yaw angles sinusoidal pitching with a positive amplitude improves the yaw stability. Conversely, at positive yaw angles, negative amplitude sinusoidal pitching further improves the yaw stability of a downwind turbine.

![Figure 8. Effect of individual pitch control (sinusoidal scheme) on yawing moment for yaw angles of 0° and ±16°.](image1)

![Figure 9. Effect of individual pitch control (sinusoidal scheme) on yaw stability coefficient for yaw angles of 0° and ±16°.](image2)

4. Discussion

The different impacts of IPC on yaw stability can be explained with the aid of the moment diagrams shown in Figure 10. The turbine tested in this study features a downwind rotor with an 8° tilt. The tilt causes a component of the shaft torque to be transmitted into the tower (\(T_1\)) which is negative for a clockwise rotating downwind wind turbine (Figure 11). It should be noted that if the rotor is tilted (and/or yawed), there is an azimuthal variation of the induced velocity. The induced velocity is smaller, when the blade points upstream than when the same blade points downstream half a revolution later. Thus, an upstream blade experiences a larger relative wind speed than the downstream blade, and thus an upstream blade generates higher loads. Furthermore, when the blade goes from \(\theta = 0°\) to \(\theta = 180°\), the axial translation of the blade is in the direction of the wind which increases the induced velocity. Conversely, from \(\theta = 180°\) to \(\theta = 0°\), the axial translation of the blade is upstream, which reduces the induced velocity. Therefore, half of the rotor (from \(\theta = 180°\) to \(\theta = 0°\)) has a higher relative velocity and generates a negative aerodynamic torque on the tower.

In the case of positive yaw (Figure 10a), the restorative aerodynamic moment (\(M_r\)) of the downwind rotor is complemented by the component of shaft torque transmitted into the tower, which also acts to restore the rotor to the zero yaw position. Consequently, for positive yaw, a downwind turbine with rotor tilt is unconditionally stable, as indicated by the negative gradient in Figure 9.
In the case of negative yaw (Figure 10b), the restorative aerodynamic moment of the downwind rotor is counteracted by the component of shaft torque transmitted into the tower, promoting further divergence of the yaw position. Thus, for negative yaw, the model turbine is conditionally stable depending on the predominance of the restorative aerodynamic moment ($M_a$).

![Figure 10](image1.png)

**Figure 10.** Plan view moment diagrams for downwind turbine with rotor tilt and: (a) positive yaw; (b) negative yaw

Due to rotor tilt, the turbine torque transmits a component into the tower.

![Figure 11](image2.png)

**Figure 11.** Due to rotor tilt, the turbine torque transmits a component into the tower.

The results of Figure 9 indicate that, for a yaw of -16°, the predominance of the restorative aerodynamic moment is reduced resulting in reduced yaw stability which is alleviated with the activation of sinusoidal IPC pitching with a positive amplitude of 1.6°. The positive sign of the amplitude ensures that, in the case of negative yaw, the windward blade is pitched towards stall, increasing the windward blade loading, while the leeward blade is pitched towards feather, reducing the leeward blade loading. Consequently, the positive amplitude augments the restorative aerodynamic moment, for the case of negative yaw. Therefore, a positive amplitude of sinusoidal pitching improves yaw stability. The negative sign of the amplitude ensures that, in the case of positive yaw, the windward blade is once again pitched towards stall, for increased blade loading, while the leeward blade is pitched towards feather, for reduced loading, promoting the restorative aerodynamic moment. Furthermore, a negative pitching amplitude of -1.6° increases the power output of the turbine by 10%. Activation of the sinusoidal pitching, with a negative amplitude, not only improves the yaw stability of the downwind turbine with rotor tilt but also increases power production.

5. Conclusion

Individual pitch control based on a sinusoidal pitching scheme that is locked to the phase of the rotor rotation further improves the superior yaw characteristics of downwind turbines compared to upwind
configurations. Yaw stability is improved with individual pitch control, when: positive pitching amplitude is employed at negative yaw angles, while at positive yaw angles, negative pitching amplitude is used.

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