Individual Blade Pitch Control for Extended Fatigue Lifetime of Multi-Megawatt Wind Turbines

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Abstract. A novel experimental study on the use of individual pitch control to extend the fatigue life of wind turbines is conducted. The experiment is accomplished using a sub-scale model of a multi-megawatt turbine in both upwind and downwind configurations in a water towing tank. It is shown that individual pitch control based on a sinusoidal pitching scheme that is locked to the phase of the rotor rotation can mitigate unsteady loads caused by the velocity variation that is induced by the effect of rotor tilt and therefore extends the fatigue lifetime of blades. A positive pitching amplitude in the case of upwind configuration and a negative pitching amplitude in the case of downwind configuration eliminate the cumulative damage fractions due to the velocity variation.

1. Introduction
The development of advanced light composite materials allows three-bladed turbines to be made considerably lighter with larger and more slender rotor blade designs, which lead to a substantially reduced cost of wind-generated electricity [1]. On one hand, the lighter and larger wind turbine blades that are more flexible, have lower modal frequencies, and on the other hand, as there is an azimuthal variation of aerodynamic loads due to wind shear and turbulence as well as azimuthal variations of induced velocity due to tilt/yaw, larger wind turbine rotors are more susceptible to failure from fatigue [2][3]. As a design life of 20 years or longer is considered for the operation of a multi-megawatt wind turbine, an improved understanding of the impact of unsteady loads on wind turbines in different operating conditions is very important [2][4][5]. It one is to reduce fatigue loads and thereby improve reliability and reduce operation/maintenance costs.

Passive and active control strategies have been considered to alleviate unsteady loads. In many studies [6][7], collective pitch control is used. However, collective pitch control is not capable of compensating for unsteady loads which vary azimuthally. A feedforward blade pitch controller added to the standard feedback control has been implemented to mitigate unsteady loads [8]. Variable pitch designs dynamically adjust the pitch position of each blade during a rotor revolution [9][10][11]. Individual blade pitch control to compensate for the variations of the aerodynamic loads has focused on load reduction [12][13]. Further, recent aero-elastic simulations suggest that individual blade pitch control may be a viable active approach to extend the fatigue life of multi-megawatt wind turbines [14][15].

The present work is novel in that experimental studies of individual pitch control on downwind and upwind turbines are conducted. The experiment is conducted using a sub-scale model of a multi-megawatt turbine in a water towing tank. The effectiveness of individual pitch control on the azimuthal variation of the rotor thrust and torque during a rotor revolution caused by the velocity variation that is
induced by the effect of rotor tilt is investigated to assess the impact on blade cumulative damage and fatigue lifetime. The comparative experimental results are complemented with theoretical analyses that are used to provide insight into the experimental findings for both upwind and downwind wind turbine configurations.

2. Methodology

The experimental study is conducted in the wind turbine test facility (WEST Facility) at ETH Zürich (Figure 1) using a 1/210 scale model of the Hitachi HTW5.0-127 wind turbine. The model’s rotor diameter \( d \) is 0.6 m, rotor tilt 8°, and the cone angle is 5°, (Figure 2). All linear dimensions are scaled down similarly based on geometrical scaling laws [16], but the root of the blade is modified to install the IPC motor and to manage loads at the blade root. The tip speed ratio of the model turbine is the same as that of the full-scale turbine. The design of the wind turbine model has been verified from BEM simulations to match the \( C_T \) and \( C_P \) of the full-scale turbine. The WEST Facility consists of a 40 m long, 1m wide and 1m deep water tank which is an open section flow channel over which a carriage is towed. Water towing tanks have been widely used for testing models of marine current turbines [17], for experiments on scaled models of marine vessels [18], tidal turbines [19][20] and wind turbines [21].

A blockage correction factor is applied as the model has a solidity ratio of 2% relative to the cross-section of the whole tank. The carriage that traverses the channel, allows the model which is mounted upside-down on the carriage to be moved through the water. A turbulence generator, shown in Figure 1, generates a freestream turbulence intensity of 8% by injecting cross-flow jets through perforations in streamlined aerofoils. For each test, the water channel is refilled to compensate for splashed water, therefore, the effect of surface waves is eliminated. At the design tip speed ratio (\( \lambda_{\text{design}} \)), the turbine rotational speed (\( N \)) is 354 rpm, and based on the blade chord length at 75% span, the Reynolds number varies over the range \( 8.2 \times 10^4 \) – \( 1.07 \times 10^5 \), depending on the operating point. Thus, the measurements are corrected for Reynolds number effects [2], as the Reynolds numbers on the full-scale wind turbine are typically between \( 5.0 \times 10^6 \) and \( 1.0 \times 10^7 \).

![Figure 1. Side view of the wind turbine test facility (WEST) at ETH Zürich.](image1)

![Figure 2. Oblique view of the subscale model wind turbine.](image2)

Independent positioning of the blades is performed with pitch motors installed in the blade root and controlled by control systems contained within the rotor hub. Power and control signals are transmitted from a nacelle-mounted stator antenna to a hub-mounted rotor antenna using a custom-built signal transmission system (Figure 2). The pitch position of each blade is updated at a frequency of 200 Hz, which allows the pitch position of each blade to be updated 30-35 times per revolution depending on the operating point, with an estimated total uncertainty of 0.24° in the commanded blade pitch position. The turbine thrust, shaft torque, tower yaw moments are measured at a rate of 10kHz using a custom-built torque shaft that is instrumented with strain gauges and telemetry. The carriage velocity and turbine speed control the tip speed ratio (\( \lambda \)). The measured driveshaft torque and turbine speed determine the produced turbine power (\( P \)) during the measurements. The power coefficient (\( C_P \)) is given as:
where $V$ is the inflow velocity of the turbine, $A$ is the cross-sectional area of the rotor, and $\rho$ is the density of water.

The bending and twisting moments are determined from the strain gauge signals measured at the root of the tower of the turbine. The thrust coefficient ($C_T$) and the moment coefficient ($C_M$) are calculated as:

\[
C_T = \frac{T}{\frac{1}{2} \rho AV^2}
\]

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

where the rotor thrust ($T$) 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 $\lambda_{design}$

| Quantity                  | Standard uncertainty (sensor characteristics) |
|----------------------------|-----------------------------------------------|
| Rotor torque               | ±0.8%                                         |
| Rotor thrust               | ±1.6%                                         |
| Power coefficient $C_P$    | ±1.9%                                         |
| Thrust coefficient $C_T$   | ±2.0%                                         |
| Yaw moment coefficient $C_M$| ±7.0%                                         |

As a turbine has rotor tilt/cone (Figure 3), there is a variation in the induced velocity ($w$) at each blade section due to the advancement/retreat of the blade into/out of the wind. The induced velocity is smaller when the blade points upstream ($\theta=0^\circ$ for downwind, $\theta=180^\circ$ for upwind) than half a revolution later when the same blade points downstream ($\theta=180^\circ$ for downwind, $\theta=0^\circ$ for upwind). This means that a blade pointing upstream is further out of the wake than a blade that is pointing downstream. On the other hand, the downstream blade (Figure 4, blue) sees a lower wind speed and thus produces lower loads than the upstream blade (Figure 4, red) [22]. Figure 4 shows the velocity triangles for a section of the blade. In this figure black, red and blue represent velocities of a blade section in intermediate ($\theta=90^\circ$ and $\theta=270^\circ$ for downwind and upwind), upstream ($\theta=0^\circ$ for downwind, $\theta=180^\circ$ for upwind), and downstream ($\theta=180^\circ$ for downwind, $\theta=0^\circ$ for upwind) positions, respectively. It is worth noting that $V$ 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 ($L$). It should also be noted that when the blade goes from top-most to bottom-most position, the axial translation of blade is into wind direction; and from bottom-most to top-most the translation is in wind direction for upwind configuration; and conversely for downwind configuration.

As shown in Figure 3, the rotor tilt for a horizontal-axis wind turbine causes an axial displacement of the blade tip ($x$):

\[
x = -R \sin \phi \cos \theta
\]

The axial displacement is dependent upon the tilt angle ($\phi$), the rotor radius ($R$), and the azimuthal position of the rotor ($\theta$) which is zero at the rotor top-most position. Revolution of the rotor, thus, causes the blade tip to advance into the wind/retreat away from the wind at an axial speed that is given by the relation:

\[
\dot{x} = R \dot{\theta} \sin \phi \sin \theta
\]
which accounts for the rotational speed of the turbine ($\dot{\theta}$).

Different strategies for individual pitch control have been developed and tested. In the present work, an individual pitch control algorithm to compensate for the 1P velocity variations induced by rotor tilt is examined. The corrective pitch adjustment (PIPC) is linearly related to the rate of advancement/retreat, which, upon integration, yields:

$$P_{IPC} = D \sin \theta$$  \hspace{1cm} (6)

where D is the pitch amplitude, and $\theta$ is the azimuthal position of the rotor which is zero at the rotor top-most position as shown in Figure 3. It is evident that there is a phase-offset of 120° and 240° for the second and third blades, respectively. It is worth noting that Figure 4 shows the reference direction of positive and negative blade pitching. Table 2 summarises the test matrix.

**Figure 3.** CW-rotating tilted upwind and downwind turbines showing axial displacement of the blade tip.

**Figure 4.** Velocity triangles at a blade section when the blade is in intermediate (black), upstream (red), and downstream (blue) positions.

| Parameter                         | Range               |
|-----------------------------------|---------------------|
| Rotor configuration               | Downwind, Upwind    |
| Yaw angle                         | $0^\circ$           |
| Tip speed ratio                   | $\lambda_{design}$  |
| Duration of each measurement      | 8 sec               |
| Pitching scheme                   | Sinusoidal          |
| Pitch amplitude (D)               | $0^\circ, \pm 0.8^\circ, \pm 1.6^\circ, \pm 2.4^\circ, \pm 3.2^\circ$ |

Table 2. Test matrix.

Fatigue damage accumulation under variable loadings conditions is assessed using the linear damage rule [23]:

$$D_i = \sum_{i=1}^{k} D_i = \sum_{i=1}^{k} \frac{n_i}{N_{RI}}$$  \hspace{1cm} (7)

where $n_i$ is the number of loading cycles at the stress level of $\sigma_i$, $N_{RI}$ is the number of cycles to failure at $\sigma_i$, $D_i$ is the cumulative damage fraction, $D_t$ is the total cumulative damage, and $k$ is the number of stress levels. As each measurement is conducted at a specific operating condition ($\lambda_{design}$ and $n_i$), in order to assess the effectiveness of individual pitch control (IPC) on the blade cumulative damage fraction, the number of cycles to failure ($N_{RI}$) are calculated with and without IPC using the Double Goodman technique [24][25]. The technique involves the subdivision of azimuthal variations into two parts: a) major cycles and b) major and minor cycles, as shown in Figure 5. The Goodman method is then applied to each part. The azimuthal variation of the measured loads (amplitude ratio or $\sigma_a/\sigma_m$) is considered in the major cycle ($\sigma_{m}$, $\sigma_a$, and $\sigma_b$) and unsteadiness of the measured loads at the rotor frequency (1P), the blade passing frequency (3P) as well as high-frequency vortex shedding of the rotor are considered in the minor cycle ($\sigma_n$) in the double Goodman method. The variance from the integral of the power spectral density of the measured unsteady loads. In the case of ‘1P’, ‘3P’, ‘Vortex’ variances the bandwidths of
integration are ±10% of the rotational speed frequency, blade passing frequency and vortex-shedding frequency (27P for this rotor), respectively and the ‘other’ variance is determined from the integral outside these bandwidths [2].

Figure 5. Unsteady stress-time relation.

3. Results
Figure 6a and b show the effect of individual pitch control (IPC) with different pitch amplitudes on power and thrust coefficient for the case of zero yaw, for downwind and upwind configurations, respectively. In Figure 6a and b, the power and thrust coefficients are normalised by the power and thrust coefficients for no yaw and no IPC for each configuration. The amplitudes (D) of the sinusoidal pitching are 0°, ±0.8°, ±1.6°, ±2.4°, and ±3.2°. In the case of downwind configuration (Figure 6a), it can be seen that the peak power is achieved with a pitching amplitude of -1.6°. The optimum pitching amplitude increases the turbine power and thrust by 11.7% and 7.8%, respectively compared to the case without pitch control. However, positive pitching amplitudes reduces power. It can also be seen that the trends in the thrust follow the trends that are seen in the power. In the case of upwind configuration (Figure 6b), it can be seen that the peak power is achieved with a pitching amplitude of +1.6°. The optimum pitching amplitude increases the turbine power and thrust by 9.4% and 0.7%, respectively compared to the case without pitch control. However, negative pitching amplitudes reduces power. It is also evident that the trends in the thrust follow the trends that are seen in the power.

As discussed above, the axial translation of blade in/into wind direction during a rotor revolution is opposite for downwind and upwind configurations, thus, the optimum pitching amplitude of individual pitch control (IPC), is opposite for downwind compared to upwind configuration.

Figure 6. Effect of sinusoidal pitching amplitudes on power and thrust coefficient for a) downwind and b) upwind configurations.
Figure 7 compares for downwind and upwind configurations the effect of individual pitch control (IPC) with different pitch amplitudes on the yaw twisting moment coefficient for the case of zero yaw. At the optimum pitching amplitude of -1.6° the yaw moment coefficient decreases by 80% in the case of downwind configuration while the optimum pitching amplitude of +1.6° decreases the amplitude of yaw moment coefficient by 2% in the case of upwind configuration.

![Figure 7](image)

**Figure 7.** Effect of sinusoidal pitching amplitudes on yaw twisting moment coefficient for downwind and upwind configuration.

The effect of IPC, with pitching amplitudes of ±1.6°, on the variations of thrust and torque during a rotor revolution for the downwind configuration is shown in Figure 8a and b, respectively. The thrust and torque are normalised by the respective mean for no yaw and no IPC. The low-frequency fluctuations or amplitude ratio of major loads is determined from the ratio of the difference between maximum and minimum loads and the average load during a rotor revolution. It can be seen in Figure 8a and b that IPC with a pitching amplitude of -1.6° reduces the amplitude ratio of rotor thrust and torque variations by 45%, 63%, respectively while a pitching amplitude of +1.6° increases the amplitude ratio of rotor thrust by 17% but decreases the amplitude ratio of rotor torque variations by 41% in the case of downwind configuration.

![Figure 8](image)

**Figure 8.** Effect of sinusoidal pitching amplitudes of ±1.6° on the variation of a) turbine thrust and b) rotor torque during a rotor revolution for downwind configuration.
The effect of IPC, with pitching amplitudes of ±1.6°, on the variations of thrust and torque during a rotor revolution for the upwind configuration is shown in Figure 9a and b, respectively. The thrust and torque are normalised by the respective mean for no yaw and no IPC. The low-frequency fluctuations or amplitude ratio of major loads is determined from the ratio of the difference between maximum and minimum loads and the average load during a rotor revolution. It can be seen in Figure 10a and b that IPC with a pitching amplitude of +1.6° reduces the amplitude ratio of rotor thrust and torque variations by 68%, 48%, respectively while a pitching amplitude of -1.6° increases the amplitude ratio of rotor thrust and torque variations by 33%, 73%, respectively in the case of upwind configuration.

![Figure 9](image_url)

**Figure 9.** Effect of sinusoidal pitching amplitudes of ±1.6° on the variation of a) turbine thrust and b) rotor torque during a rotor revolution for upwind configuration.

![Figure 10](image_url)

**Figure 10.** Effect of sinusoidal pitching amplitudes of ±1.6° on the amplitude ratio of a) turbine thrust and b) rotor torque variation during a rotor revolution for downwind and upwind configurations.

The high-frequency fluctuations or total unsteadiness is determined from the integral of the power spectral density of the measured unsteady loads. Figure 11a and b show the amplitude spectrum of shaft torque at a yaw angle of 0° for downwind and upwind configurations, respectively. The amplitudes are normalised by the maximum amplitude (1P) for each configuration. It can be seen that the contributions of the “blade passing frequency” (3P) as well as “high-frequency vortex shedding” and the “others” in
total torque unsteadiness relative to the “rotor frequency” (1P) are more in the case of downwind configuration compared to upwind. On the other hand, the rotor frequency (1P) plays the major role in high-frequency fluctuations in the case of upwind configuration while the contributions of blade passing, vortex shedding, and the others are not negligible in the case of downwind configuration, as also seen in Figures 15a and b.

Figure 12 and 13 show the effect of IPC on the amplitude spectrum of shaft torque, with the optimum pitching amplitude of -1.6° for downwind, and of +1.6° for upwind configuration, respectively. The amplitudes are normalised by the maximum amplitude (1P) for each configuration at a yaw angle of 0° with no IPC. It can be seen that in the case of downwind configuration, a pitching amplitude of -1.6° reduces the amplitudes of rotor frequency (1P), blade passing frequency (3P) by 58% and 23%, respectively and increases the amplitudes of high-frequency vortex shedding (27P) by 19%. In the case of upwind configuration, a pitching amplitude of +1.6° decreases the amplitude of rotor frequency (1P) by 43% while increases the amplitudes of the blade passing frequency (3P) and high-frequency vortex shedding (27P) by 28% and 3%, respectively.

![Figure 11. Amplitude spectrum of shaft torque for a) downwind and b) upwind configurations.](image1)

![Figure 12. Amplitude spectrum of shaft torque at yaw angle of 0° and optimum pitching amplitude of -1.6° for downwind configuration.](image2)

![Figure 13. Amplitude spectrum of shaft torque at yaw angle of 0° and optimum pitching amplitude of +1.6° for upwind configuration.](image3)
Figures 14 show the effect of IPC, with pitching amplitudes of ±1.6°, on the variance of turbine thrust in the case of zero yaw angle for downwind and upwind configurations. Figure 15a and b show the effect of IPC, with pitching amplitudes of ±1.6°, on the variance of torque in the case of zero yaw angle for downwind and upwind configurations, respectively. The contributions of each part are normalised by the value at a yaw angle of 0° with no IPC. It is evident that in the case of downwind configuration, a pitching amplitude of -1.6° reduces the total unsteadiness of measured thrust and torque variations by 51%, 53%, respectively while a pitching amplitude of +1.6° increases the total unsteadiness of measured rotor thrust by 10% but decreases total unsteadiness of measured torque by 49.5%.

In the case of upwind configuration, a pitching amplitude of +1.6° reduces the total unsteadiness of measured thrust and torque variations by 57%, 63.5%, respectively while a pitching amplitude of -1.6° increases the total unsteadiness of measured thrust and torque variations by 50%, 149%, respectively.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure14}
\caption{Effect of sinusoidal pitching amplitudes of ±1.6° on the variance of thrust for downwind and upwind configurations.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure15}
\caption{Effect of sinusoidal pitching amplitudes of ±1.6° on the variance of torque for a) downwind and b) upwind configurations.}
\end{figure}

As variation in thrust has a major impact on the flapwise bending moment and thus on the blade fatigue lifetime [26], the effectiveness of individual pitch control (IPC) on the fraction of blade cumulative damage is assessed using the double Goodman method. Table 3 shows the effect of
sinusoidal pitching amplitudes of ±1.6° on the blade cumulative damage for downwind and upwind configurations. The case of no IPC is considered as the reference case with a safety factor of 2 applied following IEC wind turbine standards for blade fatigue life analysis [27].

The analysis based on the double Goodman method shows that the blade cumulative damage fraction is reduced with an IPC pitching amplitude of -1.6° by 96% while a pitching amplitude of +1.6° increases the blade cumulative damage fraction by 140% in the case of downwind configuration. In the case of the upwind configuration, an IPC pitching amplitude of +1.6° eliminates the blade cumulative damage fraction while a pitching amplitude of -1.6° increases the blade cumulative damage fraction by 450%. As multi-megawatt wind turbines experience a wide range of loading cycles, knowing the effectiveness of IPC across all ranges of loading conditions can assess the blade fatigue lifetime improvement based on Equation 7. It is worth noting that mitigation of each blade's cumulative damage fraction increases the whole blade fatigue lifetime.

Table 3. The effect of sinusoidal pitching amplitudes of ±1.6° on the blade cumulative damage for downwind and upwind configurations

| IPC amplitude | Downwind | Upwind |
|---------------|----------|--------|
| -1.6°         | -96      | 450    |
| No IPC        | 0        | 0      |
| +1.6°         | 140      | -100   |

4. Discussion

The tilting of the rotor and coning of the blade allow for a higher allowable deflection, and thus lower blade weight, as well as an increase in the blade length. Furthermore, the effect of tower wake in the case of downwind turbines can also be reduced. While a tilted rotor and a coned blade might have higher unsteady loads and lower power production due to the velocity variation that is induced by the effect of rotor tilt and blade cone, individual pitch control as an active approach can compensate for the influence of the velocity variation.

According to Figure 3, when the blade goes from θ = 0° to θ = 90°, the axial translation of the blade is in the direction of the wind in the case of downwind configuration (that is, the positive x-direction in Figure 3) which increases the induced velocity, thus, reducing both the relative velocity and the negative incidence on outboard blade sections (Figure 4, blue). Conversely, in the case of upwind configuration, the axial translation of the blade is into the direction of the wind which reduces the induced velocity thereby, increasing both the relative velocity and the positive incidence seen by the blade (Figure 4, red). It is also evident that from θ = 180° to θ = 270°, the axial translation of the blade is into the direction of the wind in the case of downwind configuration (that is, the negative x-direction), which reduces the induced velocity thereby, increasing both the relative velocity and the positive incidence seen by the blade (Figure 4, red) and conversely for upwind configuration. Therefore, a positive (negative) sinusoidal pitching amplitude compensates for the velocity variation, which is induced by rotor tilt, by pitching the blade towards feather (stall) at an azimuthal position of θ = 90°, where the relative velocity is highest (lowest), and pitching the blade towards stall (feather) at an azimuthal position of θ = 270°, where the relative velocity is lowest (highest) for the case of upwind (downwind) configuration. Consequently, the power production is improved by a positive (negative) sinusoidal pitching amplitude (D) for the case of upwind (downwind) configuration.

Figure 16 shows the azimuthal variation of the induced velocity simulated using the FAST 5MW model of HTW5.0-126 multi-megawatt wind turbine at the λ_{design} operating condition for downwind and upwind configurations. It can be seen that for upwind configuration when the blade goes from top-most to bottom-most position, the induced velocity decreases; and from bottom-most to top-most the induced velocity increases; and conversely for downwind configuration. Furthermore, as the variation of the
induced velocity that is induced by the effect of rotor tilt and blade cone and therefore the azimuthal variation of relative velocity, is opposite for a CW-rotating tilted downwind rotors compared to upwind, the optimum amplitude of sinusoidal pitching scheme that compensates these variations, is expected to be opposite which is in agreement with experiments.

![Figure 16. Azimuthal variation of the induced velocity simulated using the FAST 5MW model of HTW5.0-126 multi-megawatt wind turbine.](image)

5. Conclusion

Individual pitch control based on a sinusoidal pitching scheme that is locked to the phase of the rotor rotation is shown to extend the fatigue lifetime of blades. For the wind turbine configurations that are examined in this work, IPC with a positive pitching amplitude in the case of upwind configuration and a negative pitching amplitude in the case of downwind configuration eliminate the cumulative damage fractions due to the velocity variation.

It is inferred that as the variation of the velocity that is induced by the effect of rotor tilt and blade cone, is opposite for a CW-rotating tilted downwind rotors compared to upwind, the optimum amplitude of sinusoidal pitching scheme is expected to be opposite which is in agreement with experiments. It should be noted that the turbine operational conditions, rotor configuration, the direction of rotation, as well as the direction of the tilt/cone angle, are the key factors in the azimuthal variation of induced velocity, and therefore, in the determination of optimum pitching amplitude of IPC.

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