Interference of Wind Turbines with Different Yaw Angles of the Upstream Wind Turbine

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This experimental study was conducted in a wind tunnel using two turbines in tandem arrangement and downstream turbine is located at \(X/D=2\). The purpose was to investigate how yawing the upstream turbine will affect the performance of the downstream turbine as well as the upstream turbine. Wind loading (thrust force), rotational frequency and power output are the parameters used to define the performance of the wind turbines used for the study. Besides, cobra probe (multi-hole pressure probe) was used to measure the flow field in the wake of the non-yawed (\(\alpha=0^\circ\)) and yawed (\(\alpha=50^\circ\)) upstream turbine. The effect of increasing the yaw angle of the upstream turbine on the overall efficiency of the wind farm (two model wind turbines) was also observed. Furthermore, overall efficiency was found to be strongly dependent on the incoming flow turbulence intensity level.

\textbf{Nomenclature}

\begin{itemize}
  \item \(D\) = wind turbine rotor diameter
  \item \(\alpha\) = upstream turbine yaw angle
  \item \(X/D\) = spacing between turbines in terms of the wind turbine rotor diameter
  \item \(Z/Z_{hub}\) = height normalized with the hub height of the wind turbine
  \item \(V\) = voltage
  \item \(R\) = resistance
  \item \(U_0, U_{\text{eff}}\) = mean and effective incoming flow speed
  \item \(A_0\) = swept area of the wind turbine rotor
  \item \(A_{\text{eff}}\) = effective swept area of the wind turbine rotor
  \item \(P\) = electrical power output (\(V^2/R\))
  \item \(F\) = axial (thrust) force
  \item \(f, f_{\text{turbine}}\) = rotational frequency of the rotor
  \item \(TSR\) = tip speed ratio
  \item \(std\) = standard deviation
\end{itemize}

\section{I. \textbf{INTRODUCTION}}

There are several factors affecting the overall power performance in a wind farm. One is the spacing between wind turbines and their arrangement pattern. As the spacing between wind turbines increases, the performance of the downstream wind turbines increases since more space gives the wake enough time for the recovery of the velocity deficit and enhanced turbulence levels, which are the main contributors for the power loss and fatigue loading especially for the downstream turbines. However, wind tunnel investigations on the wind turbine wake showed that even at twenty rotor diameters (20D) streamwise spacing, wake effects are still noticeable in the wake of a single turbine (Chamorro & Porte-Agel, 2010). Meneveau and Meyers (2012) suggested that optimal average streamwise spacing is considerably higher (15D) than currently used in wind farm implementations (7D). However, putting the turbines far apart in a wind farm is not always possible due to space and economic constraints. Wind farm layout (staggered or aligned) also plays an important role on the efficiency of wind turbines in a wind farm. Chamorro, Arndt, and Sotiropoulos (2011) found out that staggered configuration leads to improved overall power output of the wind farm on the order of 10\% in comparison to the aligned configuration with the same streamwise...
and spanwise spacing. Each turbine in the staggered layout experiences the wake of the upstream turbine over a distance of twice as much as compared to aligned layout. Thus, wake recovery occurs over longer distances in staggered case which increases the efficiency of the wind farm.

Second way of increasing the wind farm efficiency is to change the operating condition of the upstream turbines. Adaramola and Krogstad (2011) investigated that the power output of the downstream turbine can be increased by operating the upstream turbine slightly outside its optimum settings or changing the yaw angle of the upstream turbine. They found out that increasing the yaw angle of the upstream turbine up to $\alpha=30^\circ$ has a positive effect on the wind farm efficiency (maximum gain in the total power output is around 12%) for the two turbines in tandem arrangement. However, array efficiency can only be improved when the gain in the power output of the downstream turbine is greater than the loss in the power production from the yawed upstream turbine. This can be achieved only when upstream turbine operates at an appropriate yaw angle. If upstream turbine operates at higher yaw angles, a substantial loss in the power output of the upstream turbine may cause a reduction in the total power output. Pedersen et al. (2002) studied the variation of power with the yaw angle and indicated that yawing influences the power production by a $\cos^2\alpha$ relationship.

This paper presents a wind tunnel study using two turbines in tandem arrangement and downstream turbine is located at $X/D=2$. The upstream turbine was operated at different yaw angles and its effect on the wind loading, rotational frequency and power output of the turbines was investigated for different inflow conditions (no spire and spire flow). Flow field measurements were conducted in the wake of non-yawed and yawed upstream turbine in order to observe the effect of changing the yaw angle of the upstream turbine on the velocity and turbulence profiles in the wake. Furthermore, the dependence of the overall efficiency of the wind farm on the yaw angle of the upstream turbine as well as the incoming flow turbulence intensity level was analyzed.

II. EXPERIMENTAL SET-UP AND PROCEDURE

Experiments were carried out in a closed circuit wind tunnel at Iowa State University. Test section is 20m long and a cross section of 2.4m*2.3m. Spires were used to change the turbulence character of the inflow and first ten meters of the test section surface was covered with chains as a roughness element so as to simulate the atmospheric boundary conditions showing log-wind velocity profile. The flow is generated by an electric fan located downstream of the test section, and the wind speed is changed by changing the rotational frequency of the fan. In our experiments, rotational frequency is kept at 5.5 Hz.

![Figure 1. Two turbines in tandem arrangement with the upstream turbine non-yawed ($\alpha=0^\circ$) and yawed ($\alpha=50^\circ$) on a turn-table](image-url)
The 3-bladed wind turbine models used in the experiment have a diameter of 381 mm and the tower is 305 mm high with a pitch angle of 10°. The upstream turbine was set up on a turn-table in order to change its yaw angle easily and downstream turbine was installed at X/D=2 as shown in Figure 1. Two similar model wind turbines with the same characteristics were used in the experiment. Spires are used to increase the turbulence levels in the incoming flow in order to investigate the influence of the turbulence. Therefore, two different inflow conditions (no spire and spire) were investigated during the experiments (see Figure 2).

Figure 2. Simulation of atmospheric boundary layer conditions in the wind tunnel using spires and chains

Figure 3 shows the measured profiles of normalized flow velocity and turbulence intensity for two flow cases: spire and no spire flow cases. Hub height (Z/Z_{hub}=1) turbulence intensity for the no spire case is around 8%; however, for the spire case, turbulence intensity goes up to 18% at the hub height.

Figure 3. Measured vertical profiles of the normalized mean velocity (U/U_{hub}) and turbulence intensity (I_{uu})
As the air goes through the rotor of the model wind turbine, blades start to rotate and electrical voltage through the DC motor installed inside the nacelle was measured under different loading (resistance ranging from 1 ohm to 1000 ohm) conditions. Resistance was adjusted by using a variable resistance box connected to the DC motor via special wiring equipment. Then electrical power output ($V^2/R$) was calculated. Optimum power output for the turbines was calculated at a resistance value of $R=6$ ohm during the experiments. Sampling frequency is 1 kHz with sampling time of 180 seconds.

JR3 Force/Moment transducer was installed underneath the model wind turbine to measure the dynamic loads (all three components of aerodynamic forces and the moment about each axis) acting on the wind turbine. The precision of the force-moment sensor cell for force measurements is $\pm0.25\%$ of the full range (40 N). During the tests, sampling frequency is 1 kHz with sampling time of 120 seconds.

During the experiments, turbine angular velocity was also measured using the Monarch Instrument Optical Tachometer. Fast Fourier Transform (FFT) analysis of voltage time series taken from the tachometer was used to obtain the turbine angular velocity.

Furthermore, multi-hole pressure (cobra) probe was used to obtain detailed flow field measurements in the wake of the upstream turbine and effect of upstream turbine yaw angle on the wake profile was also investigated. Besides, cobra probe measurements in the near wake of a single turbine (X/D=0.2) at the top-tip turbine height were done in order to identify the signature of tip vortices on the power spectra of the fluctuations in the velocity components and observe the yawing effect on the vortex shedding frequency.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Increasing the yaw angle of the upstream turbine leads to a decrease in the effective wind speed component which is perpendicular to the rotational plane of the wind turbine rotor. The effective wind speed ($U_{eff}$) changes with the yaw angle of the wind turbine (see Figure 4) and the variation is related to the cosine of the incoming flow velocity ($U_0$). Moreover, projected swept area of the wind turbine rotor is also reduced with the cosine of the yaw angle of the wind turbine.

Figure 4. A schematic of two turbines (upstream turbine yaw angle, $\alpha$) in tandem arrangement

\[ U_{eff} = U_0 \times \cos(\alpha) \]
\[ A_{eff} = A_0 \times \cos(\alpha) \]

Therefore, upstream turbine operating in different yaw angles extracts less power from the incoming flow. Figure 5 clearly shows that by increasing the yaw angle of the upstream turbine, there is a corresponding decrease in the power output of the turbine. Pedersen et al. (2002) indicated that the variation of power with the yaw angle is very close to the square of cosine ($\cos^2$) of the yaw angle after computational and experimental analysis. However, according to the solely experimental results on a model wind turbine, as shown in Figure 5, the decrease in the
power output is substantially higher, making $\cos^2$ - relation is too optimistic especially at higher yaw angles. Instead, $\cos^3$ - relation comes out to be a better approximate for the effect of yaw angle on the power reduction.

Figure 5. Variation in the relative power output of the upstream turbine at various yaw angles for the no spire and spire flow cases

Furthermore, no significant effect of the incoming flow turbulence level was observed on the power reduction with the yaw angle. However, a slight difference can be seen in the slopes of the curves for the spire and no spire flow. The upstream turbine in the no spire - less turbulence - flow is more likely to be affected severely from the misaligned flow especially at higher yaw angles.

Figure 6. Variation in the relative thrust force (wind loading) of the upstream turbine at various yaw angles for the no spire and spire flow cases

The effect of yaw angle on the wind loading (thrust force acting on the turbine) is also plotted in Figure 6. The variations in the wind loading and in the power output of the upstream turbine with increasing upstream turbine yaw angle are showing almost the same overall trend with a major difference. Although $\cos^2$ - relation is too optimistic for the power output variation, it fits almost perfect with the variation in the wind loading. Therefore, increasing the yaw angle of a turbine influences the power by the cube of cosine ($\cos^3$) of the yaw angle and the wind loading by
the square of cosine (cos²) of the yaw angle. Apparently, the effect of yawing is more severe on the power output of the wind turbine in comparison to its effect on the wind loading. This can be explained by the dependence of power output and wind loading on the incoming flow speed (U₀), where power is proportional to the cube of the incoming wind speed (P ∝ U₀³) and wind loading is proportional to the square of the incoming wind speed (F ∝ U₀²). By increasing the yaw angle of the turbine, effective wind speed component is reduced by the cosine of the yaw angle so that it affects the power output (P ∝ cos²α) and the wind loading (F ∝ cos²α) of the wind turbine.

Figure 7. Variation in the upstream turbine rotational speed at various yaw angles for the no spire and spire flow cases

Figure 8. Power spectrum of the measured voltage from the optical tachometer
The change in the power output of a turbine can also be inferred from its rotational frequency. The rotational frequency was measured using an optical tachometer (direct) and through the signatures of tip vortices on the power spectrum of velocity fluctuations at the turbine top-tip height and at X/D=0.2 (indirect).

Figure 8 shows the amplitude versus frequency plots for a turbine at yaw angles of $\alpha=0^\circ$ and $\alpha=50^\circ$ for different incoming flow conditions (spire and no spire). It was obtained from the FFT (Fast Fourier Transform) analysis of the voltage time series recorded from the tachometer. Dominant peak in the amplitude can be identified at the primary frequency which corresponds to the rotational frequency of the wind turbine. As inferred from Figure 7 and Figure 8, a significant decrease is observed in the rotational frequency of the turbine operating at a yaw angle of $\alpha=50^\circ$ compared to the non-yawed turbine. Tip Speed Ratio (TSR) decreases from 3.3 for a non-yawed turbine to 1.7 for a turbine at a yaw angle of $\alpha=50^\circ$. Furthermore, the effect of the spires on the rotational frequency of the turbine is also shown. Spires not only increase the turbulence intensity of the incoming flow but also obstruct the flow thereby reduce the mean flow speed. The former effect causes fluctuations in the power output of the wind turbine and rotational frequency as well. Figure 9 shows the amplitude of oscillations in the power output of the upstream turbine. It was calculated by dividing the standard deviation (std) in the power output to the average power output (an analogy to the turbulence intensity calculation). No significant change is observed in the amplitude of power fluctuations with the increase in the yaw angle. However, due to the highly turbulent nature of spire flow, fluctuations in the power output are more pronounced for the spire flow. Unsurprisingly, the amplitude of power fluctuations is in good agreement with the turbulence intensity levels throughout the rotor of the wind turbine. The latter degrades the performance of the wind turbine by decreasing the power output and rotational frequency of the wind turbine. The reduction in the rotational speed due to the presence of spires can be detected in Figure 7 when compared to the no spire flow.

![Figure 9. Amplitude of fluctuations in the upstream turbine power output for the no spire and spire flow cases](image)

Figure 9 shows the power spectra of the velocity fluctuations in streamwise, spanwise and vertical directions at top-tip height and X/D=0.2 downwind of the upstream turbine. The effects of tip vortices are not stronger for the spire flow since the signatures of the tip vortices are dissipated rapidly due to higher turbulence. However, as shown in Figure 10, the vortex shedding frequency associated with the tip vortices is clearly observed in the no spire flow as a consequence of relatively low turbulence levels. The change in the primary vortex shedding frequency (first peak, at $3f_{\text{turbine}}$, where $f_{\text{turbine}}$ is the rotational frequency of the rotor) of a turbine at different yaw angles can also be seen in the Figure 10. Harmonic frequencies are also detected at the multiples of the shedding frequency. It is also evident from the Figure 10 that tip vortices have stronger effects on the power spectra of vertical velocity fluctuations.
Figure 10. Power spectra of fluctuations in streamwise (top), spanwise (middle) and vertical (bottom) velocity components at top-tip height and at X/D=0.2
After studying the influence of yaw angle on the wind loading, rotational frequency and power output of the upstream turbine, next step is to study how changing the yaw angle of an upstream turbine can affect the downstream flow and the downstream turbine located at X/D=2.

Figure 11. Mean normalized velocity and turbulence intensity profile at X/D=2 behind the wind turbine for the no spire (top) and spire flow (bottom) cases

It can be inferred from Figure 11 that increasing the yaw angle of an upstream turbine reduces the velocity deficit in the wake since the wake is deflected sideways by yawing the upstream turbine. However, this effect is more pronounced for relatively less turbulent - no spire - flow due to the fact that high turbulence in the flow triggers the vertical mixing mechanism making the wake recover faster. It is also clear from the turbulence intensity distribution in the wake that increasing the yaw angle of the upstream turbine does not make any significant changes in the turbulent intensity profile of the wake. However, it is quite discernible in the no spire flow that turbulence intensity profile in the wake of the yawed upstream turbine is slightly shifted down; therefore, turbulence intensity is increased below the hub height and reduced above the hub height compared to the wake of the non-yawed wind turbine.
In the tandem arrangement of two turbines with X/D=2 spacing, the performance of the downstream turbine is severely affected from the upstream turbine wake. The power loss in the downstream turbine will go up to 40% for the no spire flow. However, the spire flow has enhanced turbulence levels which triggers the vertical turbulent mixing mechanism so that wake recovers faster for the spire case. Thus, power loss can be reduced down to 23% for the downstream turbine (see Figure 12).

Although increasing the yaw angle of the upstream turbine leads to a reduction in both the wind loading and the power output of the upstream turbine, downstream turbine can take advantage of that situation since it is no longer going to be under the direct effect of the upstream turbine wake. Therefore, downstream turbine sees comparably higher wind speeds and it will experience higher wind loads and generate more power. Figure 12 clearly indicates that by increasing the yaw angle of the upstream turbine, there is a corresponding increase in the performance of the downstream turbine. The gain in the power output of the downstream turbine by increasing the upstream turbine yaw angle is influenced by the turbulence character of the incoming flow. It can be also inferred from Figure 12 that the gain in the power output of the downstream turbine is around 29% for the spire flow and 40% for the no spire flow at an upstream turbine yaw angle of $\alpha=50^\circ$ (the largest yaw angle used in the experiment) in comparison to the non-yawed upstream turbine position. This reveals the fact that increasing the yaw angle of the upstream turbine has a strong effect on the power output of the downstream turbine especially for the flows with lower turbulence intensity levels.
The effect of increasing the yaw angle of the upstream turbine on the overall power output from two turbines in tandem arrangement at X/D=2 spacing is also investigated for different incoming flow conditions. Figure 13 shows how the overall efficiency of the wind farm (two model wind turbines in tandem arrangement) is affected by the yaw angle of the upstream turbine for the no spire and spire flow cases. The effect of the turbulence character of the incoming flow on the overall power output from the two turbines with increasing upstream turbine yaw angle can be also deduced from Figure 13.

It is shown in Figure 13 that increasing the yaw angle of the upstream turbine does not improve the overall efficiency of the wind farm in highly turbulent (spire) flow and even the overall efficiency tends to decrease with increasing upstream yaw angle. A gradual decrease in the wind farm efficiency can be observed for the spire flow case. Total efficiency decreases around 14% at an upstream yaw angle of $\alpha=30^{\circ}$ and the decrease is approximately 26% at $\alpha=50^{\circ}$. However, in relatively low turbulent (no spire) flow, as inferred from the Figure 13, wind farm efficiency can be improved up to 6% if the upstream turbine operates at an appropriate yaw angle. For a yaw angle of $\alpha=10^{\circ}$ and at X/D = 2 spacing, a 6% gain in the overall efficiency is observed compared to the non-yawed upstream position. Furthermore, even at $\alpha=20^{\circ}$, wind farm efficiency is increased approximately 3%. However, further increase in the yaw angle of the upstream turbine leads to a reduction in the wind farm efficiency since the drop in the power output of the upstream turbine becomes more dominant on the overall power output.

The results presented in the paper support the idea, which was also mentioned by Adaramola and Krogstad (2011) that the application of yaw angle adjustment for the upstream turbines in large wind farms will improve the wind farm efficiency. However, the ambient turbulent intensity level surrounding the wind farm also plays an important role on the array efficiency. Although highly turbulent flow tends to improve the overall efficiency of the wind farm (see Figure 13, efficiency in the spire flow is increased about 10% compared to the no spire flow for non-yawed upstream turbine position), yawing the upstream turbine does not have a positive effect on the overall efficiency of the wind farm in highly turbulent flow conditions.

IV. CONCLUSION

The results showed that by operating the upstream turbine at an appropriate yaw angle, the wind loading and power output for the downstream turbine can be improved due to the fact that yawing the upstream turbine changes the direction of the wake generated by the upstream turbine so that downstream turbine experiences considerably higher wind speeds and no longer suffers from the severe effects of the upstream wake. Although increasing the yaw angle of the upstream turbine increases the performance of the downstream turbine, a corresponding decrease occurs in the performance of the upstream turbine. Thus, upstream turbine should operate at an appropriate yaw angle in order to increase the overall power output from two turbines.

In this study, the wind farm efficiency increased up to 6% at an upstream yaw angle of $\alpha=10^{\circ}$. It was also observed that effect of increasing the yaw angle of the upstream turbine on the overall wind farm efficiency is strongly dependent on the incoming flow turbulence intensity level. Although higher turbulence in the flow tends to increase the wind farm efficiency, yawing the upstream turbine has a negative impact on the overall efficiency.

Future study plan involves simulating a wind farm with more rows of turbines and investigate how the strategy of operating the upstream turbines in the first row at an appropriate yaw angle (e.g. at $\alpha=10^{\circ}$ ) will affect the performance of the turbines in the downstream rows and wind farm efficiency as well.

REFERENCES


