Analysis of Traditional Yaw Measurements

Curiosity is the very basis of education and if you tell me that curiosity killed the cat, I say only the cat died nobly.

Arnold Edinborough

Limitations of Post-Rotor Yaw Measurements

In a recent analysis we demonstrated two key points.

We demonstrated that the wind speed measurement of the post-rotor anemometer had an error related to the wash produced by the rotating blades. As such, free wind measurements are much better to determine wind speed for calculating the output power curves of turbines than the wind speed measurements via nacelle-mounted anemometers.

In general, the industry does accept that the speed measurement of an anemometer located in the post-rotor flow is flawed, and that measurement of the wind in front of the turbine is superior.

The second was that by switching to yaw control based upon free wind characteristics real and substantial power increases can be achieved.

In general, the industry is dubious of the amount of extra power that can be generated by changing yaw control.

A reading of the literature suggests that yaw angle isn't nearly as exciting as pitch control. Perhaps that's because yaw is sort of like yawn? Maybe it's because the industry thinks the vanes behind the turbine are nicely calibrated and believes the simple COS^3 math and doesn't see how it could really matter all that much. Or perhaps the turbine manufacturers just don't like to talk about how silly it is to point a multi-million dollar turbine based upon measuring the wind direction right after a gigantic spinning propeller?

However, when yaw is not set properly, power is lost, but more importantly, stresses are placed onto turbines. Because of the potential magnitude of the economics of these issues, we believe spending some time asking fundamental questions about yaw, and then using actual data from field turbines to try to answer these questions, might be of some benefit to the operators of wind turbines trying to maximize their economic viability.

In this paper, we look in greater detail at the yaw angle of the turbine relative to the wind.

Key question: *Based upon data from the nacelle-mounted measurement system, what are the characteristics of the current yaw measurement system?*

Key question: *Does the rotating vortex post-rotor have an effect on measurement of yaw angle?*

Key question: *Can rotor-induced errors in yaw measurements be corrected so that a good control system can be designed?*

Our world needs us, the wind turbine industry, to produce power, cleanly, efficiently and at low cost. Here at BlueScout, our contribution to the wind industry is to use our understanding of optics to provide a fundamentally deeper understanding of the wind resource - to produce substantial, repeatable increases in the output power of wind turbines.

Synopsis

A BlueScout Optical Control System (OCS), Generation I, is mounted upon an operating utility scale wind turbine. The yaw angle of the turbine is studied in a variety of different ways to better understand the physics of basing control decisions upon measurements of the post-rotor flow.

Data Set and Analytic Tools

The data set is large, approximately 500 MB, composed of 335,000 data points taken at 1 second spacing. SAS JMP used as the statistical analytic tool. The dataset includes output from the OCS, two sonic anemometers (giving both wind speed and wind direction), turbine state, ambient temperature, output power, and absolute yaw position.

Starting Simple

A wind turbine produces the most power when it is pointed directly in the wind. As the turbine moves away from facing the wind, two things happen- it produces less power and endures more mechanical stress.

Let's begin by looking at the distribution of output power against the measured wind angle. We start with the data from the OCS.

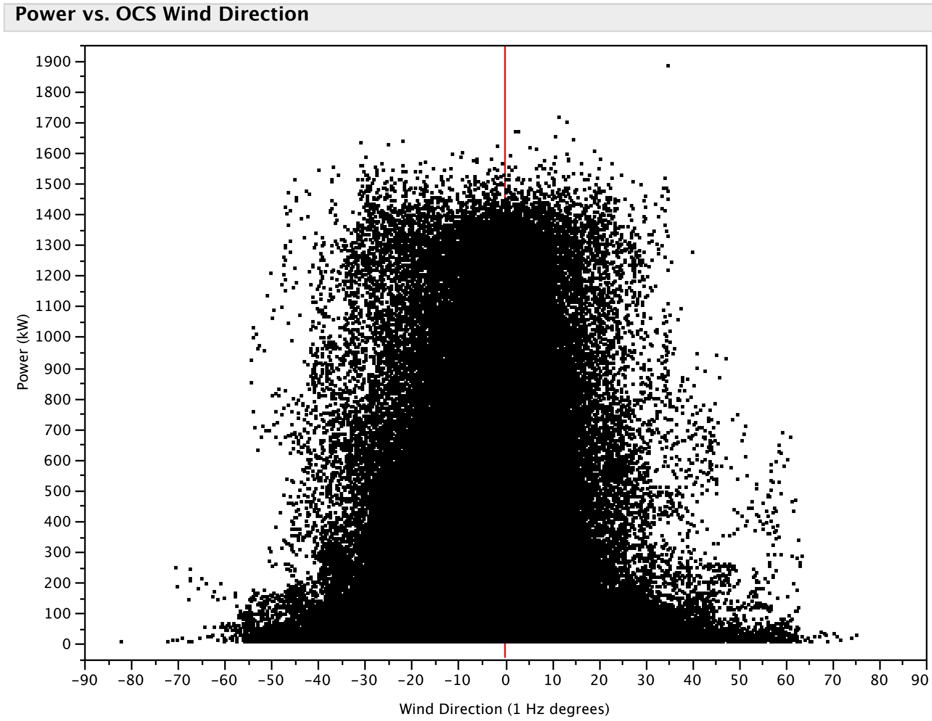

Figure 1 A scatter plot of the output power of the turbine vs. wind angle as measured by the OCS.

In general, the data of Figure 1 fits our intuition. The measured output power is roughly capped at 1.5 MW. The power of the turbine falls off as the angle of the wind relative to the turbine (yaw error) increases. The data is symmetric, and roughly centered at zero.

Now the same data set is used to do a scatter plot with the angle being measured by one of the sonic anemometers. Again, the power peaks at about 1.5 MW. Again, the power falls off as the post-rotor angle increases. The scatter plot is narrower than what is measured in the free stream. The data set is not symmetric, with the center of power distribution now being ~10-15 degrees. Further, the amount of angular offset changes with turbine power. Finally, the measurement of post-rotor angle shows very sparse data for angles less than -30 degrees.

This paper focuses upon understanding this behavior in greater detail.

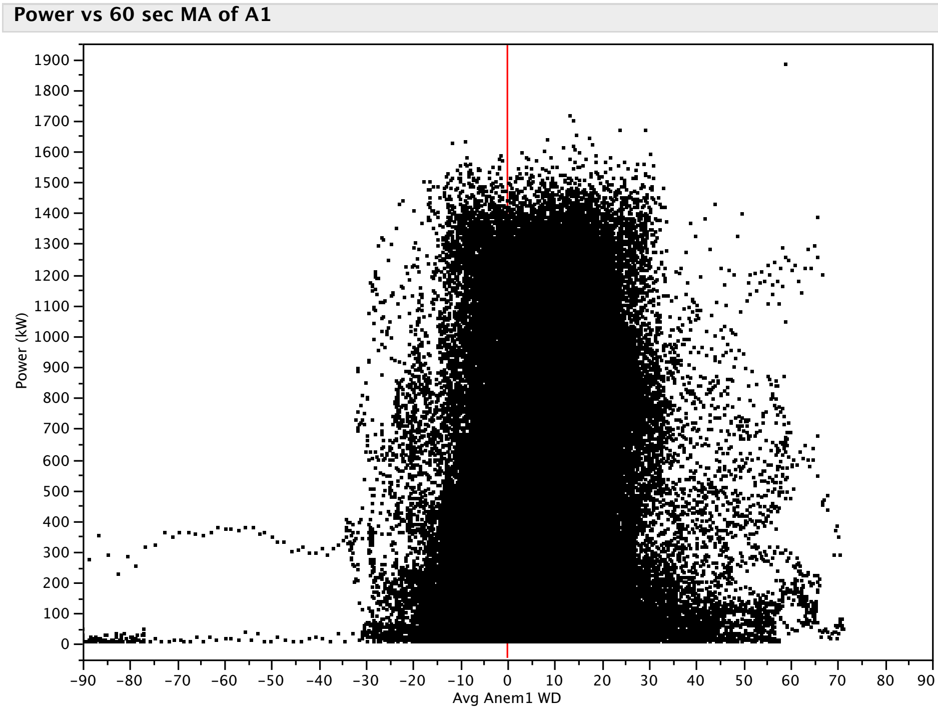

Figure 2 A scatter plot of power vs. post-rotor wind angle measured by the anemometer. The data is not symmetric, with the center of the distribution being offset by ~10 degrees.

Post-Rotor Yaw Measurements

Let's start with basics. The turbine is going to produce the most power when it faces the wind. The fundamental task of yaw control is to aim the turbine into the wind. We look first at the distribution of wind angles, as judged by post-rotor wind as measured by the sonic anemometer, while the legacy yaw control is operating the turbine. In this work, we do not look to the OCS to judge the legacy control system, rather we look closely at the post-rotor measurements and use very simple physical arguments to understand the efficacy of trying to figure out a yaw angle while sitting in the vortex of the rotor.

It should be noted that when we do compare the OCS to the legacy measurement system, that comparison compares two different attributes. The first is the type of measurement device. While the physics of wind measurement with LIDAR are a bit different than measurements based upon a physical wind vane or an acoustic anemometer, we believe that each of these devices can be calibrated and do a fine job of measuring wind characteristics. The second, and we believe much more significant, is the physical position of the wind that is being measured. The sonic anemometer (or wind vane) is behind the rotor. As such, it is situated in place with a constant rotational bias. This effect, where the direction of the airflow is partially due to the wind and partially due to the rotating blades is one of the items that we wish to investigate in this paper.

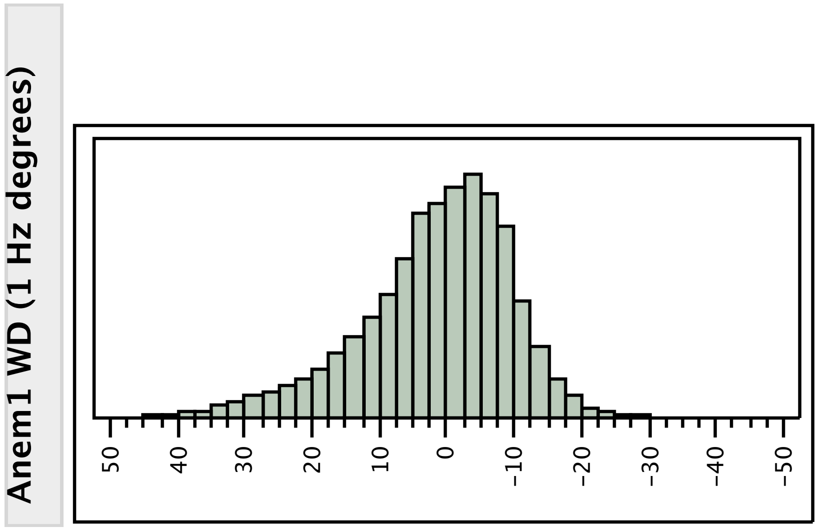

Figure 3 The measured distribution of wind angles, as measured in the post-rotor wind flow. The bottom is degrees. The distribution has mean and median of 1.55 and 0 degrees, respectively. The standard deviation is 11.3 degrees.

Figure 3 shows the distribution of yaw angles, as measured by the acoustic anemometer. In looking at this distribution, we note that the mean and median are very well centered, at 1.55 degrees and 0 degrees, respectively. The standard deviation is 11.3 degrees. The distribution is not symmetric, as one would expect for a device in the rotor wash of the turbine. This implies that the measurement system *is non-linear with respect to wind angle.*

Figure 4 shows the same distribution, under legacy control, but now measured by the OCS on the free wind in front of the turbine. This distribution is roughly symmetric, but is now centered about 8 degrees off of the zero axis of the OCS.

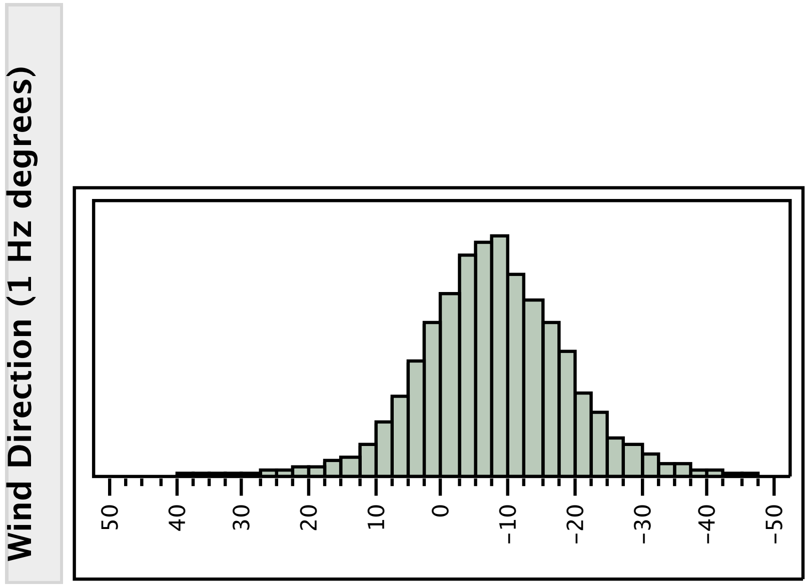

Figure 4 The distribution of yaw angles with respect to the free wind, as measured by the OCS. The turbine is under legacy control. The distribution is roughly symmetric. The mean of the distribution is -7.8 degrees, with a standard deviation of 11.8 degrees.

Key Point: *The legacy control does a good job of centering the yaw angle as judged by post-rotor wind measured by the sonic anemometer. The yaw angle is measured to be asymmetric, with standard deviation of ~11.3 degrees.*

Key Point: *Under legacy control, the OCS measures a free-wind angle distribution that is about as broad as distribution measured by the sonic anemometer, but centered at -7.8 degrees. This distribution is symmetric.*

Now we consider the distributions when the turbine sets yaw based on the free wind angle in front of the turbine as measured by the OCS. We again start with the yaw-angle measured post-rotor by the sonic anemometer.

As the anemometer is measuring wind in the rotating rotor wash, the measurement shows asymmetry. The distribution is shifted away from zero and is substantially broadened. Given that the distribution of yaw angle, as measured by the post rotor flow, is worsened under OCS control, the turbine should produce less power under OCS control if the post rotor yaw measurement is correct.

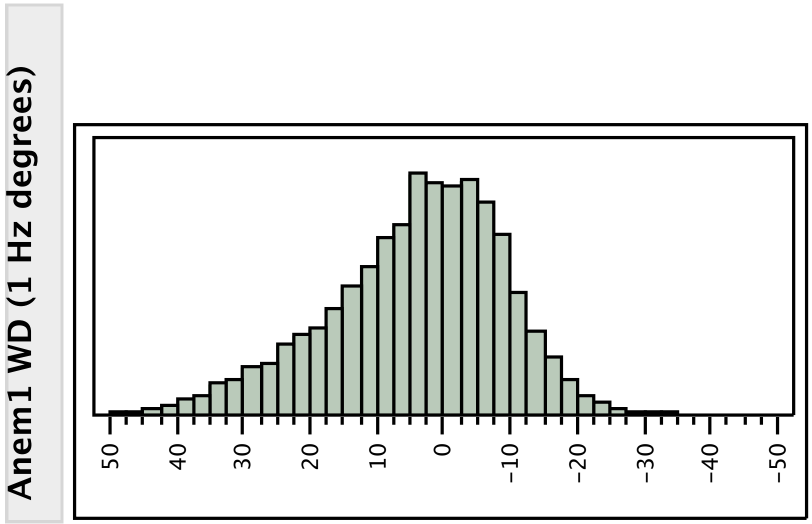

Figure 5 The distribution of yaw angles, measured in the post-rotor flow by the sonic anemometer. The distribution is still asymmetry, as before, but the mean of the distribution has been shifted to 4.2 degrees. Under OCS control the distribution measured by the anemometer significantly broadens, with standard deviation increasing to 13.6 degrees.

The yaw angle distributions, using the free wind in front of the turbine as measured by the OCS, is shown below. The distribution is still symmetric, but is now much better centered, with a distribution that is substantially narrower than when the turbine is under legacy control. Given that the distribution of yaw angle, as measured by the free wind flow, is improved under OCS control, the turbine should produce more power under OCS control if the OCS measurements are correct.

The curious reader says, “whoa! Those paragraphs can’t both be right!” While we don’t wish this paper to deal with power production under different control regimes, the fact that the yaw angle distributions are very different when controlled differently does imply that the power that will be extracted from the wind, and the mechanical wear and tear upon the turbine, will be different in the different control regimes (i.e., under OCS control or legacy control). *Spoken bluntly, yaw control does matter.*

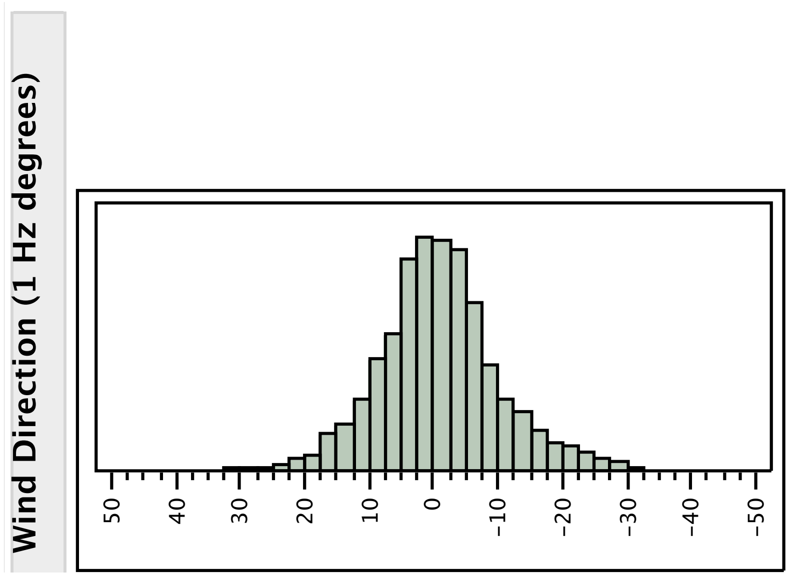

Figure 6 The distribution of yaw angles, based upon the free wind in front of the turbine as measured by the OCS. The distribution is shifted, with the mean now at -0.9 degrees. The distribution of yaw angle is substantially narrower, with standard deviation now down to 9.7 degrees.

Key point: *Under OCS control, the distribution of yaw angle, as measured by the OCS, is center at ~0 degrees and is made substantially narrower.*

Key point: *Under OCS control, the distribution of yaw angle, as measured post-rotor, is moved away from being centered at zero, and is substantially broadened.*

Key point: *The yaw distributions, as measured by either the OCS or the legacy post-rotor anemometer, change substantially between the two control schemes. Because yaw angle directly impacts the performance of the wind turbine the performance of the turbine will be different under OCS control than legacy control.*

Practical Yaw Optimization Using Post-Rotor Yaw Measurements

It is tempting to look at the data just presented and think that a neat controls protocol could fix up the problems associated with a control algorithm based upon post-rotor wind measurements.

To investigate this, we begin by grouping the data into angular buckets, -25 to -15, -15 to -5, -5 to 5, 5 to 15, 15 to 25, and 25 to 35 degrees. Next, we compute power curves for each angular group. For clarity, this is shown by coloring the data points by which angular bucket they fall into as shown below.

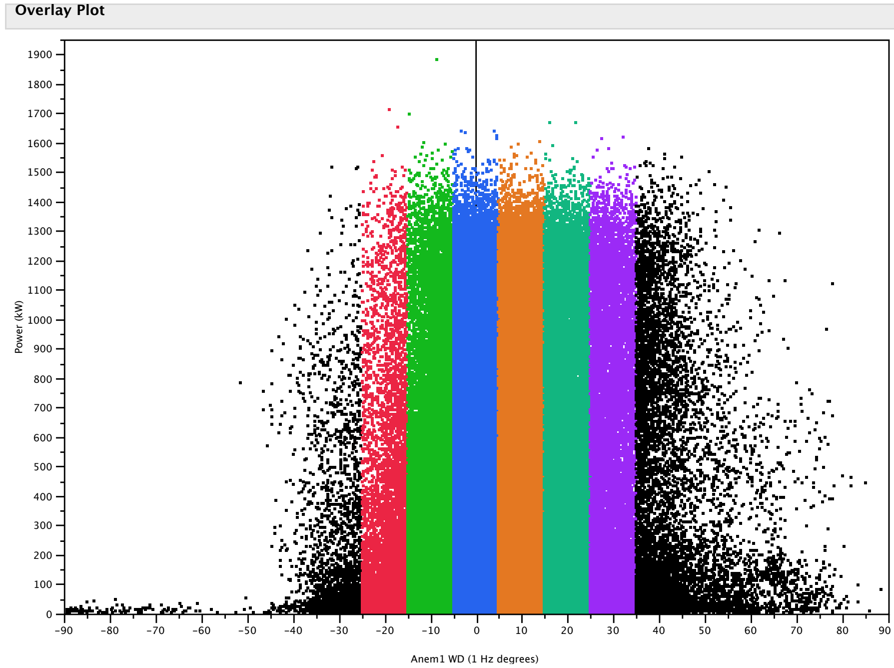

Figure 7 The scatterplot of wind angle as measured by the post-rotor anemometer. The color-coding of the data points indicates the angle bins.

We next cut power curves for each of the angle buckets. As expected, the efficiency of the turbine changes with angle. *However, the angle where maximum power occurs changes with output power as shown in the following figure*. Given that the turbine always produces maximum power with a zero yaw angle, we conclude that the anemometer has an angular error that is dependent upon wind speed, and that a simple offset is not capable of fixing the post-rotor yaw angle error.

For this turbine, the optimum angle for power extraction, as measured by the sonic anemometer, varies with power. Obviously, the true "optimal" angle, with respect to the free wind in front of the turbine, is zero degrees, implying that a wind measurement device in the post-rotor turbulence has a rotor-induced error, at a true angle of zero degrees to the turbine, which is dependent upon the operational state of the turbine. This angular error has variance of approximately *40 degrees* over the operation of this turbine.

Thus, the measurement of yaw angle is non-linear with respect to both yaw angle and wind speed.

For this turbine, the post-rotor error crosses zero at ~10 m/s wind speed. In heavy wind, the legacy turbine control will be misaligned to the wind by ~20 degrees.

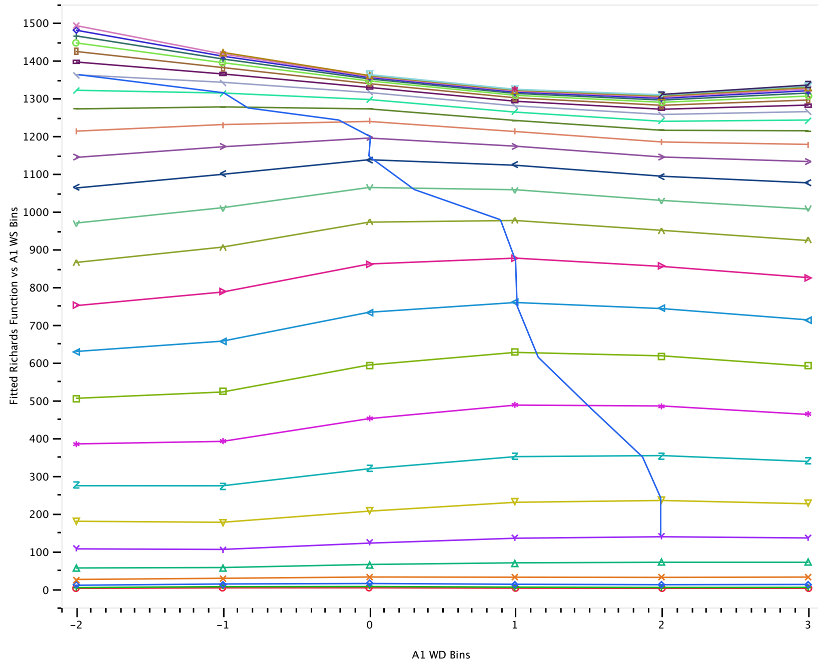

Figure 8 A contour plot showing curves of constant wind speed. The blue line indicates the angle of maximum power production. Each integer unit on the X-axis corresponds to 10 degrees, indicating that the angle of maximum power varies substantially.

Key Point: *The rotation of the blades induces an error into the measurement of yaw angle. This error changes as the wind speed increases. The turbine has no way of sensing this error.*

Key Point: *There is no magic offset angle for the anemometer. A control algorithm that uses a constant offset angle to optimize power based upon post-rotor wind measurements will sub-optimize the power production.*

Key Point: *In moderate to heavy wind, the turbine is misaligned to the wind by ~20 degrees, resulting in increased operational stresses.*

Key Point: *These conclusions are based simply upon the legacy post-rotor sonic anemometer and upon the idea that turbine power is maximized at zero yaw angle.*