Spinner Anemometry

an Innovative Wind Measurement Concept

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SPINNER ANEMOMETRY - AN INNOVATIVE WIND MEASUREMENT CONCEPT

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SUMMARY:

An innovative and new concept for measurements of wind on a wind turbine has been developed and implemented. The new concept has potentials for improved tools for wind turbine control, and verification of power performance and loads. The present method of measuring wind on wind turbines is by the use of nacelle anemometry, in which wind speed and wind direction are measured with sensors mounted on the upper side of the nacelle. The sensors comprise a cup anemometer and a wind vane or a 2D sonic sensor, and often the sensors are made redundant by mounting two sets side by side. Nacelle anemometry gives input to the control system for yaw and pitch control, and for start up and shut down, as well as for performance verification. Meanwhile, nacelle anemometry is hampered by the fact that it is positioned behind the rotor, and therefore measures wind that is influenced by the wakes of blade roots, the blade root vortices, the flow over the nacelle, and the mounting arrangement for the nacelle anemometry. The new concept measures the wind with the use of the spinner in front of the rotor, and thus eliminates most disadvantages of nacelle anemometry. The principle of the new concept is an integration of the spinner and wind speed sensors into a hybrid wind measurement system. The concept has been tested by development of prototype 1D sonic sensors. These have been mounted on a 300kW spinner configuration on a tripod. The spinner anemometer has been tested both in a large wind tunnel, and in the field. The sensors have then been transferred to a spinner on a 3,6MW wind turbine, and initial measurements have been made during operation of the wind turbine. The wind tunnel tests confirm the concept ideas. Free field comparison to a 3D sonic anemometer seems to give comparable data, and full scale measurements on the 3,6MW wind turbine indicate great potentials for spinner anemometry, including wind turbine control, and verification of power performance and loads.

INTRODUCTION

The present methodology of measuring wind on wind turbines is based on nacelle anemometry, in which wind speed and wind direction are measured with sensors mounted on the upper side of the nacelle. Typically the sensors comprise a cup anemometer and a wind vane or a 2D sonic sensor, and often they are doubled for redundancy, see Figure 1. Nacelle anemometry gives input to the control system for yaw control, start up and shut down, as well as for power performance verification. A typical arrangement of nacelle anemometry is shown in Figure 1.

Figure 1 Arrangement of nacelle anemometry on the back of the nacelle of a modern wind turbines. The instruments are mounted on a reasonably solid support structure with lightning protection covering the instruments and with redundant mounting of cup anemometers and wind vanes

Figure 2 Arrangement of wind sensing instruments on a fixed arm extending from the spinner of a BOUNUS 55kW wind turbine

Meanwhile, nacelle anemometry is hampered by the fact that it is positioned behind the rotor. Nacelle anemometers measure wind that is influenced by the wakes of the blade roots, the blade root vortices the flow over the nacelle, and the mounting arrangement of the nacelle anemometry. These effects may cause weak yawing characteristics, especially in complex terrain, which leads to losses in electric power and increased loads.

AN INNOVATIVE WIND MEASUREMENT CONCEPT

The new measurement concept measures wind on the wind turbine in the virgin wind flow in front of the rotor. Here, the measurement is almost undisturbed by the rotor and the nacelle. Some disturbance from the blade roots and the overall inflow of the rotor may influence the measurements, though. The mounting of wind sensors in front of the rotor was indeed made by Bonus on their 55kW to 100kW wind turbines in the 80's, as shown in Figure 2. The anemometry was mounted on an arm extending from the shaft and reaching out in front of the spinner. The tube for the instruments had to be mounted and fixed behind the shaft, and was led through the shaft and the spinner to a distance from the spinner of about the size of the spinner in order to be adequately free of the influence of the spinner.

The idea arose to use the spinner itself as a sensor for wind measurements (patented). The shape of a spinner nose on most wind turbines is not much different from the shape of the nose of a pitot-tube, though the size is somewhat larger. A pitot-tube nose is spherical, and the measurement theory of the pitot-tube is based on the sphere, as well as the theory of the spinner anemometer. One way to measure the wind speed could therefore be to measure the pressure differences from five holes in the spinner, similar to a five-hole pitot-tube. There are some disadvantages of this, though. One is the sensitivity of pressure tabs to rain and icing, and the other is the sensitivity to rotation.

A better measurement method is to measure the wind itself over the spinner, and to use sonic anemometry, which is a conventional and robust measurement principle [1]. Sonic anemometry also works under icing conditions with internal heating [2]. A spinner anemometer can thus typically consist of three 1D sonic wind speed sensors, mounted symmetrically at the front of the spinner, as shown in Figure 3. The sonic sensors are mounted with the sensor paths in plane with the rotor axis and with the sonic paths tilted somewhat backwards to allow wind to come undisturbed into the sensor paths. In this way, the wind component on the sensors due to rotation is cancelled out, and only the wind along the axis direction is measured. The tilted-back configuration of the 1D sonic sensor also allows the sensor to be sufficiently narrow so that it can be mounted from the inside of the spinner through a hole in the mounting fitting on the spinner. By converting the three wind measurements of the 1D sonic wind speed sensors to a representative spinner scalar wind, an angle of attack relative to the rotor axis and an azimuth angle on the spinner, all three wind components relative to a spinner coordinate system are determined. In order to convert the wind components from the spinner coordinate system to a non-rotating stationary coordinate system, fixed with the nacelle, an accurate azimuth angle, or rotor position, also has to be measured, and used for the conversion.

The basic physical principle of the spinner anemometer is based on the air flow over the spinner. Directional wind speeds are measured in the three fixed positions above the boundary layer over the spinner surface, see Figure 3. When the wind angle of attack on the spinner changes, the three wind speeds at the sensors change. This systematic change is used to measure the wind angles of attack. The principle can be easily understood by study of Figure 4 for a plane flow over a sphere that transforms into a cylinder.

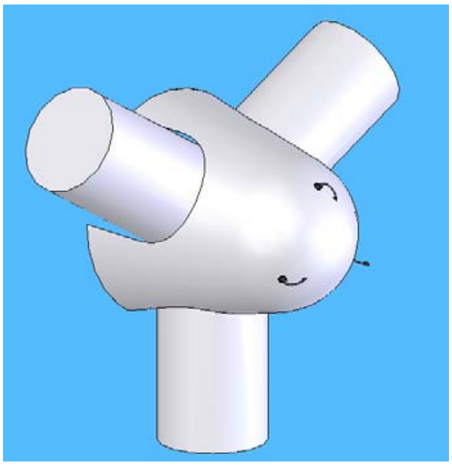

Figure 3 The concept of a spinner anemometer with three 1D sonic sensors mounted on the front part of the spinner. The spinner is in this figure shown with a spherical nose with a transitionto to a conical part.

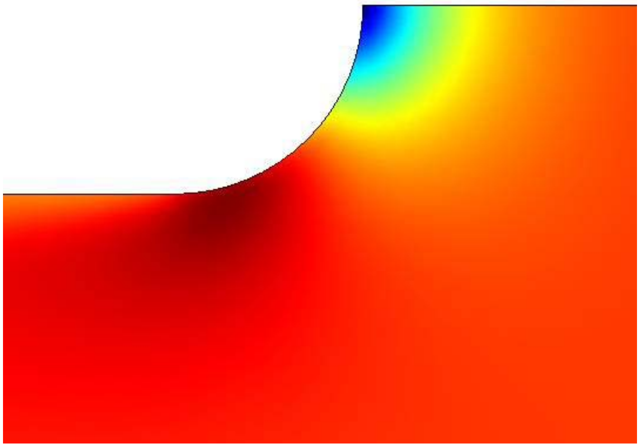

Figure 4 Wind speed contours around a rotational symmetric spinner without rotation (wind from the right). The spinner has a spherical nose that transform into a cylinder. Notice the zero wind speed at the stagnation point at the nose (blue), the "free" wind speed (orange-red) at about 50º position over the surface of the spherical part, and the "overspeeding" (dark) close to the transition from spherical to cylindrical part (COMSOL simulation).

At the front of the spinner the wind speed is zero at the stagnation point, but at an angle of about 50º on the spherical part the wind speed over the surface is about the same as the free wind speed. Above 50º the wind speed accelerates still further and at about 90º the wind speed is at a maximum. This means that when the wind direction changes, a sonic sensor on one side will see and acceleration, while a sonic sensor on the opposite side will see a deceleration. The relative difference is a function of the angle of attack, and this function can be used to determine the exact wind direction. For three axi-symmetric mounted sensors a somewhat more complicated function can be derived, which make use of the principle, and assures that all three wind speed components are determined.

The spinner anemometer concept comprises additional advantages. The rotation of the spinner anemometer has the natural consequence that each sonic sensor, over time, has to measure the same average values. This unique feature can be used to make "internal" calibrations of the sensors against each other. This means, that measurements of the wind inflow angles can be made very accurate. A consequence of the same feature, that each sonic sensor can be used separately by averaging over time, makes the system accurate, redundant and very robust. Even with two wind sensors down, the system can give an accurate average wind measurement. Accurate measurement of the wind inflow angles is very important for wind turbines. The yaw error, i.e. the horizontal average inflow angle, influences the power production. Investigations of the power performance losses [3] indicate that the power output of a wind turbine is reduced with a $\cos^2$-function of the yaw error. This means a reduction of power of 1%, 3%, 7% and 22% for systematic average yaw errors of 5º, 10º, 15º and 20º, respectively.

CONCEPT TESTS IN WIND TUNNEL

A test of the measurement concept was made in a large 4x4 m^2 wind tunnel. A small spinner (for a 300kW wind turbine) with a spherical nose and a transition to a conical part was mounted horizontally on a shaft on a tripod. The shaft could be rotated up to about 15rpm. The tripod was mounted on a turn-table in the floor which could be yawed to change angle of attach of the wind on the spinner. A cup anemometer was mounted at the lower left corner of the inlet to the test section. The arrangement in the wind tunnel is shown in Figure 5, and a detailed view of the sonic sensors mounted on the spinner is shown in Figure 6. Two different prototypes of 1D sonic sensors were produced and tested. One type had relatively thick sensor heads, as seen mounted in Figure 5. The other type had slender sensor heads, as seen in Figure 6.

Figure 5 Arrangement for concept tests in a 4x4 m^2 wind tunnel. The spinner is seen yawed to -90º and the sonic sensors can be seen on the nose of the spinner. One sensor is horizontal in which position the sensor wind speed was measured with a sweep from -90º to 90º and related to the cup anemometer wind speed measured in the lower left corner of the inlet to the open test section.

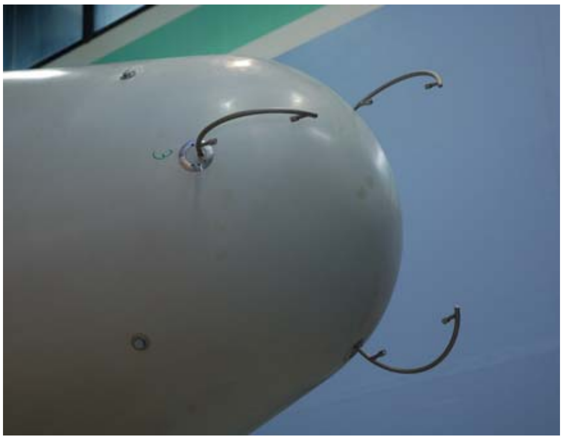

Figure 6 Prototype 1D sonic wind sensors mounted from the inside of the spinner through the fittings on a 300kW wind turbine spinner. The sensor paths are tilted backwards in order for the wind to flow undisturbed into the paths. This eliminates flow distortion due to the sensor heads for the most important wind directions when the wind turbine is yawed into the wind.

At first, measurements were made without rotation in order to "calibrate" expected flow characteristics. The spinner was positioned so that one probe was horizontal for the static test. Figure 7 shows the probe wind speed relative to the cup wind speed at about 8m/s, measured at different yaw positions, and with a continuous yaw sweep. Figure 8 shows yaw sweeps at three different tunnel wind speeds. Figure 9 and 10 show measurements during rotation at 20º and 10º yaw and a wind speed of 9m/s for the "thick" type of sonic sensors.

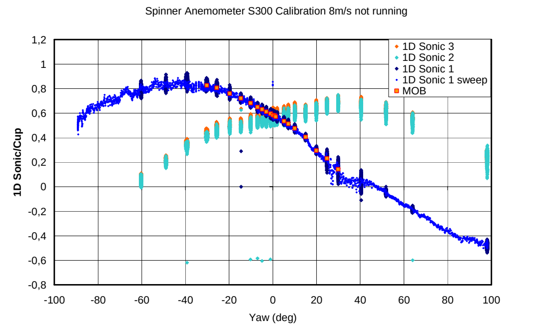

Figure 7 Static measurements of 1D "thick" sonic sensor wind speeds relative to cup anemometer wind speed at fixed positions and with a yaw sweep

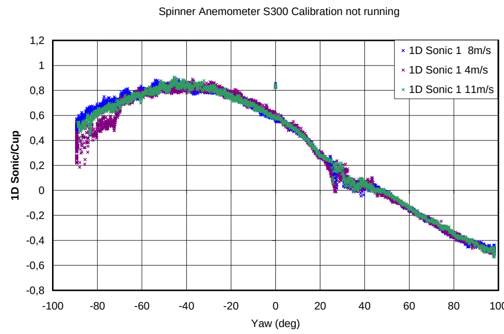

Figure 8 Static measurements of 1D "thick" sonic sensor wind speeds relative to cup anemometer wind speed at three different wind speeds for yaw sweeps

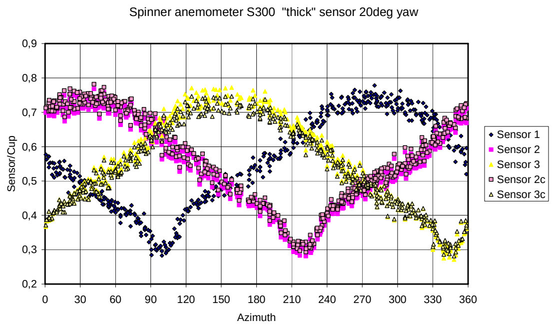

Figure 9 Scatter of measurements of 1D sonic sensor wind speeds relative to cup anemometer wind speed during rotation at a yaw angle of 20º and with "thick" sensor heads. Index c indicates data have had an "internal" calibration

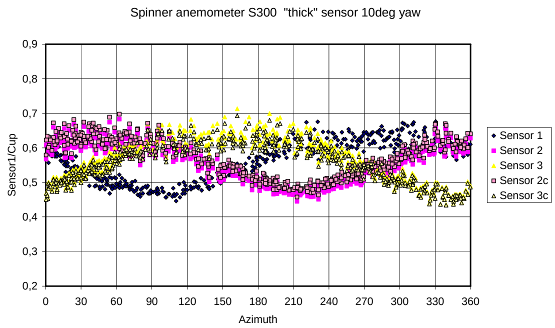

Figure 10 Scatter of measurements of 1D sonic sensor wind speeds relative to cup anemometer wind speed during rotation at a yaw angle of 10º and with "thick" sensor heads. Index c indicates data have had an "internal" calibration

COMPARISON TESTS WITH 3D SONIC ANEMOMETER

The small 300kW spinner anemometer, as used in the wind tunnel tests, was tested under field conditions at the Risø test site with the "slender" sensor type. A 3D Gill Windmaster sonic anemometer was mounted with the sensor heads at same height and about three meters to the side and a little in front of the spinner anemometer for comparison. Measurements were made while rotating at 15rpm. The spinner and the sonic sensors are shown in Figure 11. The whole arrangement is shown in Figure 12.

The flow over the spinner was calculated with ELLIPSYS3 CFD software, and the flow speeds along the 1D sonic paths were determined. These calculations were used as "calibration" values for the spinner anemometer, and were basis for the conversion from the three measured 1D sonic wind speeds into a scalar wind speed, a yaw angle and a flow inclination angle. The three wind parameters were then compared to the corresponding parameters from the 3D sonic anemometer. The comparison of the parameters is shown in Figure 13, 14 and 15. Figure 13 shows comparison of scalar winds, while Figure 14 shows the yaw angle, and Figure 15 the flow inclination angle.

The red curve on the figures is not a simple moving average. The red curve is an average of individual measurements of each sonic sensor averaging over 1000 samples, which corresponds to 29 seconds, or about half a minute. The measured wind speeds and wind direction by the two anemometers seem to follow each other quite good. The most of the variations are the same for the two sensors. Especially the wind flow direction measurements compare very well. The wind direction changes seen in Figure 14 are followed very detailed by both sensors. The average absolute wind speed of the 3D sonic, as seen in Figure 13, is a little lower than the spinner anemometer wind speed. The difference is about 2%.

Figure 11 The spinner anemometer in comparison to a 3D sonic anemometer

Figure 12 Arrangement of the spinner anemometer comparison with the sonic anemometer at the test station at Risø

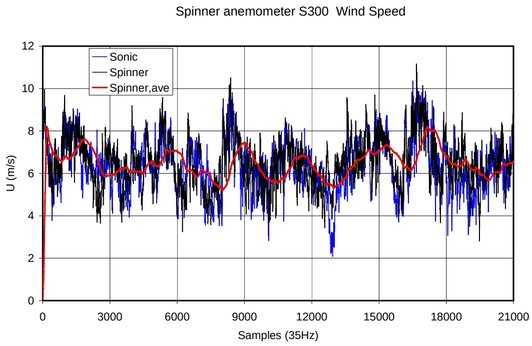

Figure 13 Comparison of measured wind speed at 35Hz sampling rate (10min of data) of spinner anemometer and 3D sonic anemometer

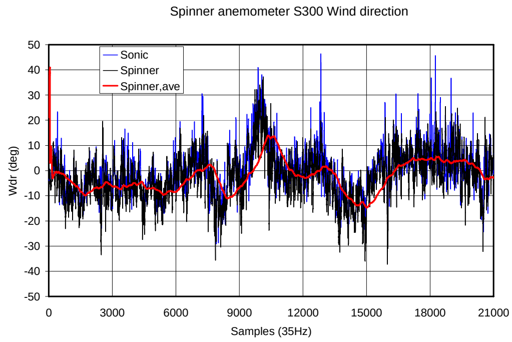

Figure 14 Comparison of measured horizontal inflow angle at 35Hz sampling rate (10min of data) of spinner anemometer and 3D sonic anemometer

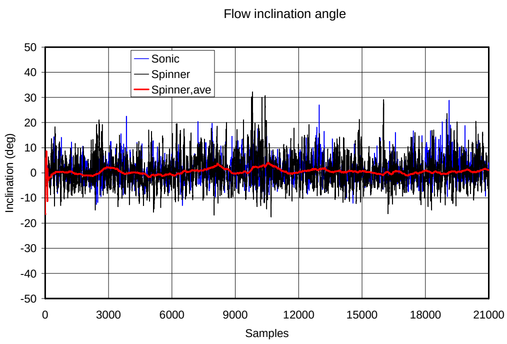

Figure 15 Comparison of measured vertical inflow angle at 35Hz sampling rate (10min of data) of spinner anemometer and 3D sonic anemometer

FULL SCALE TESTS

The 1D "slender" sonic wind sensors were mounted on a 3,6MW wind turbine at the Høvsøre test site, see Figure 16. The sensors and the fittings to hold the sensors were all mounted from the inside of the spinner, to which there was access through the hub. The sensors and fittings were mounted under conditions of 15-20m/s wind and heavy rain. Holes for the fittings were drilled from the inside by use of a template, and the fittings were hoisted from the ground through the holes. The mounted sensors and the measurement box, as seen from the inside of the spinner, are shown in Figure 17. The rotor position was measured with accelerometers mounted in the hub.

Figure 16 The three 1D sonic wind sensors mounted on the 3,6MW wind turbine spinner at the Risø Høvsøre test station

Figure 17 The mounted sensors and the measurement box, seen from the inside of the spinner.

Just after the mounting of the spinner anemometer and the measurement system for data acquisition, the wind turbine was started up for normal operation at about 7m/s wind. During operation, the wind turbine was first yawed about 50º CW as seen from above, and afterwards it was yawed about 50º CCW. Figure 18 shows wind speed measured with the spinner anemometer during a 10min time series, while Figure 19 shows measured wind direction, and Figure 20 shows measured flow inclination angle (the flow inclination angle was adjusted with withdrawal of the shaft tilt angle). The measured 1D sonic wind speeds were converted with CFD "calibration" data, as for the 300kW spinner. For the 3,6MW case, the contour of the spinner and the nacelle were taken into account in the ELLIPSYS3 calculations, while the blade roots and the tower were not taken into account.

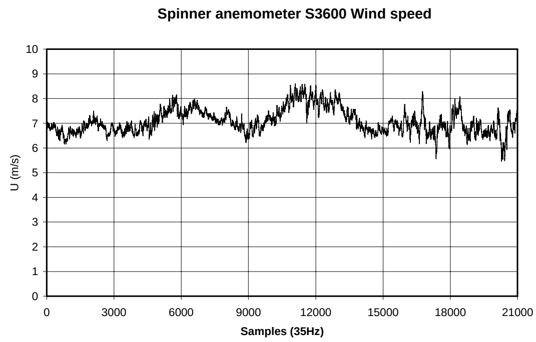

Figure 18 Measured wind speed with the spinner anemometer on the 3,6MW wind turbine over a 10min time series at 35Hz sampling rate

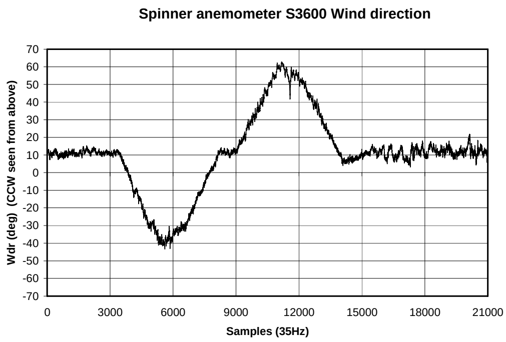

Figure 19 Measured relative wind direction with the spinner anemometer on the 3,6MW wind turbine over a 10min time series at 35Hz sampling rate

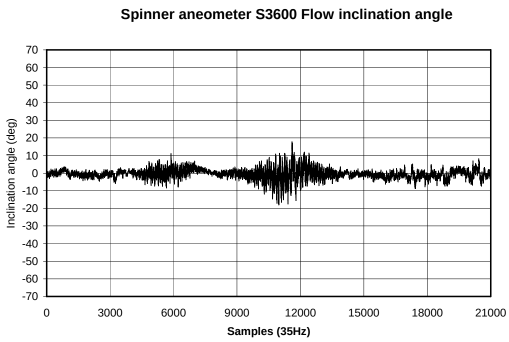

Figure 20 Measured flow inclination angle with the spinner anemometer on the 3,6MW wind turbine over a 10min time series at 35Hz sampling rate

DISCUSSION

The results of the wind tunnel concept tests, as shown in Figure 7 and 8 show a reasonably high sensitivity to flow angle of the spinner anemometer. The sensitivity is about 1% change of sonic to cup wind speed per degree yaw. This means, that at 10m/s wind speed, a one degree yaw change will change the sonic wind by 0,1m/s. The sonic sensor itself has a sensitivity of 0,01m/s, so the overall spinner anemometer sensitivity to yaw change is quite good. Figure 7 shows somewhat scatter of the data due to the turbulence in the wind tunnel, which during the tests was about 2.2%. In the region 15º to 45º yaw, the scatter increases, and the curve has a broad drop. At these yaw angles the flow at the sonic sensor is quite parallel to the sonic sensor path, and this will cause separated air flow in the wake of the sensor head to be in the sensor path. This will cause a systematic error in the measurement, the so-called sensor head shadow effect. It is well-known from literature [4]. The effect was expected to be more pronounced on the small 300kW spinner, because the sonic sensors were actually designed for a much larger spinner. On the 300kW spinner, the sonic paths actually protrude quite far above the spinner surface, which causes relatively higher flow angle changes at the sensor path with yaw changes. The effect is much lower on larger spinners, because the flow will be more parallel to the surface than in this case. The sensor head shadow effect is also quite visible in Figure 9 at 20º yaw, where the three sensors show a drop for each revolution. The effect seems almost gone in Figure 10, where the yaw is reduced to 10º, and the curves seem sinusoidal shaped. Unfortunately, the same measurements at 20º yaw were not performed with the "slender" sonic sensors, but the small dimensions of the sensors heads will under all circumstances reduce the sensor head shadow effect significantly.

The idea of using the spinner for wind measurements of a wind turbine were satisfied with the wind tunnel investigations. The sensor head shadow effect was shown to be quite influential with the "thick" sensors, which it also is on regular 3D sonic anemometers. Thus, it was decided only to use the "slender" sonic sensors on the following experiments.

The comparison of the spinner anemometer with the 3D sonic shows that the principles of the spinner anemometer work well. The spinner anemometer is actually able to measure fast scanned data comparable to the sonic. As long as the spinner anemometer is comparable in size to the sonic this may be right, but when the size of the spinner increases, the fast scanned measurements may reduce the response at the higher frequencies. The 3,6MW spinner is about 250% larger in size, so this may be an effect that can be investigated on this spinner.

The prototype 1D sonic sensors were designed for spinners to MW size wind turbines, but they seem to work well even on a 300kW wind turbine. The analysis of the measurements on the 3,6MW wind turbine is very limited at present. Only the analysis of the first measurements is available. These data indicates, on the other hand, that the principle also seems to work satisfactorily on this spinner. Figure 19 shows very detailed how the yawing of the wind turbine is influencing the measured wind direction of the spinner anemometer. The yawing of 50º to each side is very clear in the figure. It is also seen, that the wind turbine returns to a yaw angle of about 10º after each time it has yawed out. This indicates that further improvement of yawing capability can be achieved with the use of the spinner anemometer.

Figure 20 shows the flow inclination angle, which as expected, is around horizontal 0º. When the wind turbine is yawed out, the scatter seems to increase significantly. The reason for this has not been analysed at present, but during mounting of the sonic sensors it was discovered that two of the sensors were mounted with at least 2º directional error due to a simple mounting mistake, and this may cause some variations at high yaw angles.

CONCLUSIONS

The idea of using the spinner of a wind turbine for wind measurements has been investigated theoretically and experimentally. A specific configuration of a spinner anemometer with a 300kW wind turbine spinner and three prototype 1D sonic sensors has been investigated in detail. Wind tunnel tests have been performed, and a field comparison with an ordinary 3D sonic anemometer was made. The sonic sensors have then been transferred to a 3,6MW wind turbine, and initial tests have been made.

The wind tunnel tests confirm that the concept of using the spinner of a wind turbine has great potentials for wind and wind direction measurements. The field comparison tests show that measurements of a spinner anemometer are comparable to 3D sonic measurements. This may indicate that spinner anemometers have good potentials for turbulence measurements on wind turbines, which is important for verification of power performance and especially loads. Full scale tests on a 3,6MW wind turbine imply that a spinner anemometer is able to measure the relative wind direction quite accurate. No comparable measurements have been presented to free wind mast measurements at present, but such measurements must be made to confirm the implications.

In general, it must be concluded, that the spinner anemometer concept has quite significant potentials in wind turbine control, and verification of power performance and loads.

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