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Using Rotor or Tip Speed in the Acoustical Analysis of Small Wind Turbines

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Abstract

Acoustical noise data have been collected and analyzed on small wind turbines used for water pumping at the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, TX. This acoustical analysis differed from previous research in that the data were analyzed with rotor or tip speed being the independent variable in addition to analyzing the data with wind speed as the independent variable. Acoustical noise generation was analyzed for two different wind turbines which were tested with different blades. The averaging period for acoustical noise data was one second instead of one minute (smallest time increment recommended in IEC wind turbine noise standard) since the sound pressure level of small stand-alone wind turbines can vary significantly over just a few seconds. Disconnecting the wind turbine from the water pump motor by the pump controller was shown to significantly increase the noise of the wind turbine.

I. Introduction

Currently the International Electrotechnical Commission (IEC) 61400-11 wind turbine noise standard[1] (subsequently referred to as the "noise standard") requires sound pressure level (SPL) data to be collected simultaneously either with wind speed data, or with wind turbine power output data (from which wind speed can be estimated). This standard specifies that the minimum averaging period for the data collection is 1-minute. This time period is adequate for large utility scale wind turbines since their rotor speed is closely correlated to wind speed for most of their operating range (the range where rotor speed would not correlate well with wind speed is in start up and braking) . However, the rotor speed of most small stand-alone (e.g. no utility grid tie) wind turbines is not constant over a 1-minute averaging period, which leads to significant scatter in a graph of SPL with respect to wind speed. In 2003, researchers at the National Renewable Energy Laboratory (NREL) realized that the time averaging period of 1-minute was too large for small stand-alone wind turbines, so they used an averaging period of 10 seconds instead of 1-minute[2]. At USDA-ARS-CPRL we decided to collect the noise data for an averaging period of one second to see if the scatter in the SPL data could be further reduced[3-4]. We've recently collected acoustical data on a small grid tied wind turbine (Southwest Windpower[λ] 1.8 kW Skystream) using an average time period of 10 seconds, and the data scatter was significantly less than on our small stand-alone wind turbines, so a 1-minute time period may be adequate for small grid-tied wind turbines. Future papers will report acoustical noise data on the Southwest Windpower 1.8 kW Skystream and the 0.9 kW Whisper 100.

The noise standard also specifies the location of the sound level meter (SLM) and the anemometer with respect to the wind turbine location. The SLM is to be located on a sound board (at least 1 meter in diameter) and a specific distance (tower height + distance from centerline of hub to blade tip) downwind from the base of the tower. The anemometer is to be located a distance of 2-to-4 rotor diameters upwind from the wind turbine at a height of 10 meters. If the anemometer is at a different height, the wind speed data must be corrected from that height to a 10 meter height. Figure 1 shows a picture of the set up for the 1 kW wind turbine analyzed in this paper. The noise standard specifies the primary windscreen (the purpose of the primary windscreen is to keep the microphone from picking up wind noise blowing across the microphone) to be 9 cm (3.5 in) in diameter. Prior to noise data collection on our wind systems, we found out that NREL was using an 18 cm diameter windscreen as their primary windscreen. Therefore, in order to be able to compare our noise measurements with those at NREL, we decided to collect data using the 18 cm diameter primary windscreen. A comparison of the SPL data collected with the two

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different windscreens (9 and 18 cm) is shown in Fig. 2. The difference in SPL measured with the two different windscreens was very small (mean values differed less than 1 dB), so the SPL collected with the 18 cm diameter windscreen is expected to be almost identical to that measured with the 9 cm diameter windscreen.

Figure 1. Acoustical SPL collection (blue secondary windscreen at lower left corner) and anemometer wind speed collection (sonic anemometer at top of portable 10 m tower on right) for SWWP 1 kW wind turbines (hub height = 19.2 m).

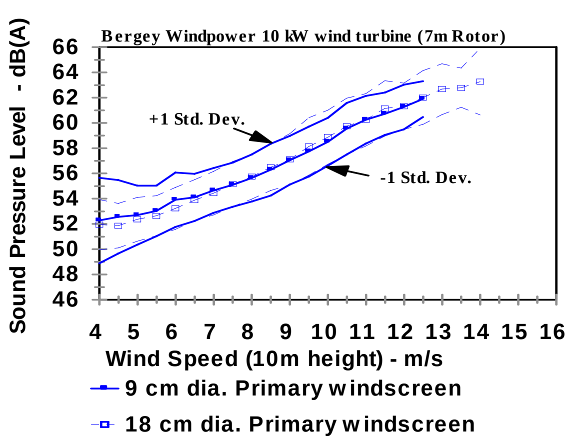

Figure 2. Comparison of SPL measured with two different primary windscreens.

The two wind turbines which were analyzed for acoustical sound emission in this paper were the Southwest Windpower H-80/Whisper 200 1 kW water pumping wind turbine and the Bergey Windpower 10 kW water pumping wind turbine. The Southwest Windpower (SWWP) Whisper 200 wind turbine is a modified version (improved rotor and yaw bearings, improved slip rings, adjustable voltage settings, and shorter stiffer blade set) of the SWWP H-80 wind turbine, but in regards to noise, the main difference was the blade set. The Bergey 10 kW water pumping version wind turbine (hub height = 18.6 meters) is no longer manufactured. These wind turbines were tested with different blades and the noise analysis in this paper will be on the noise difference between the different blades. It should also be mentioned that the noise data were collected during normal operation of the wind powered water pumping systems, and the systems were not modified (e.g. allowing wind turbine to run offline intentionally to collect more of this type of data). The noise standard specifies that "secondary windscreen may be used when it is necessary to obtain an adequate signal-to-noise ratio at low frequencies in high winds."

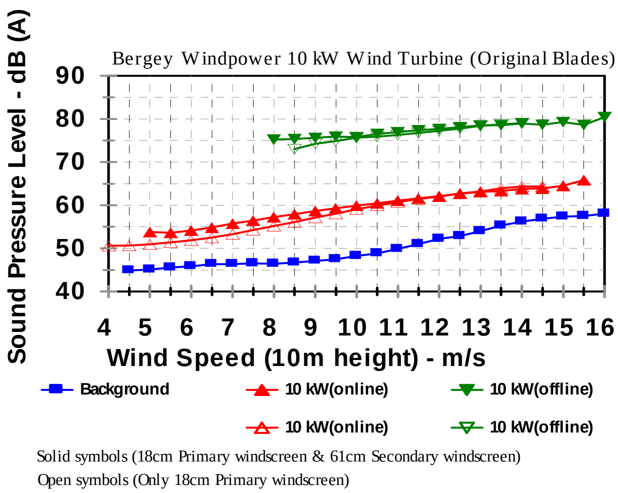

Figure 3. Comparison of SPL for primary windscreen and for both primary & secondary windscreens.

The definition of "high winds" is not given, but since the wind speed range specified for noise collection is 6 to 10 m/s, we assumed that above 10 m/s an additional secondary windscreen might be required, so we collected half the SPL data with a primary windscreen and the other half with both primary and secondary windscreens. The secondary windscreen is specified to be at least 45 cm in diameter, and ours was 61 cm in diameter. Figure 3 shows a comparison of the Bergey 10 kW wind turbine with just an 18 cm primary windscreen and with both an 18 cm primary windscreen and a 61 cm secondary windscreen. Since most of the high wind turbine noise occurs at high wind speeds, all of the noise analysis shown in the remainder of the paper is with both primary and secondary windscreens.

II. Results

A. Southwest Windpower H-80/Whisper 200 Acoustical Noise Analysis

Noise emission data were collected on the SWWP H-80 wind turbine with two different wind turbine blades and for the SWWP Whisper 200 with a third blade (Fig. 4).

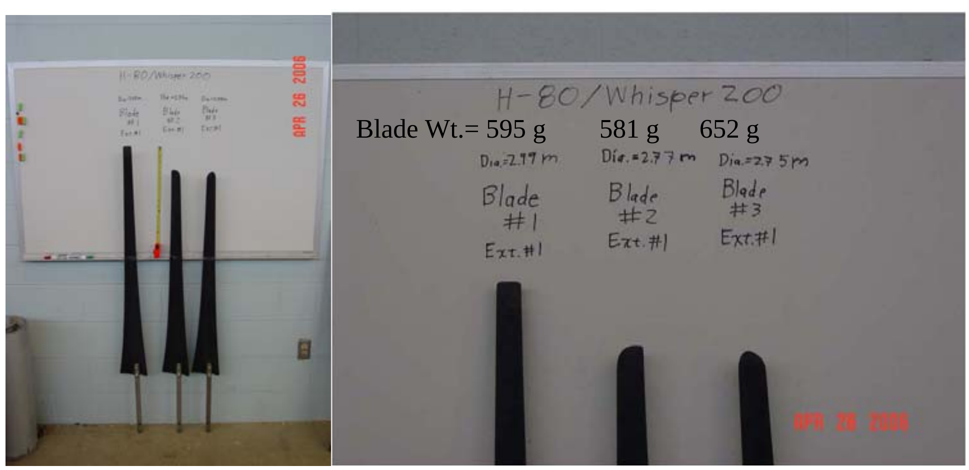

Figure 4. Blades tested on SWWP H-80 and Whisper 200 during acoustical noise data collection.

All three blades used the same airfoil (Wortmann FX 63-137) and were manufactured by the same process (injection molding where resin and fiber are injected into the mold and cured under pressure). The blade chord and twist distributions of all 3 blades varied similarly with span. Blade #1 (3m diameter, 0.595 kg) and Blade #2 (2.77m diameter, 0.581 kg) were tested on the H-80 wind turbine. Blade #3 (2.75m diameter, 0.652 kg) was tested on the Whisper 200 wind turbine. Although Blade #3 is almost the same diameter as Blade #2, it is more rigid (e.g. less likely to flutter) compared to Blade #2 due to increased fiber content. The blades were first attached to square metal tubes (0.33m long, 0.75 kg) before they were attached to the wind turbine hub. The tip shape was different on all three blades, but we feel the tip shape is of secondary importance compared to size and/or weight differences between the blades.

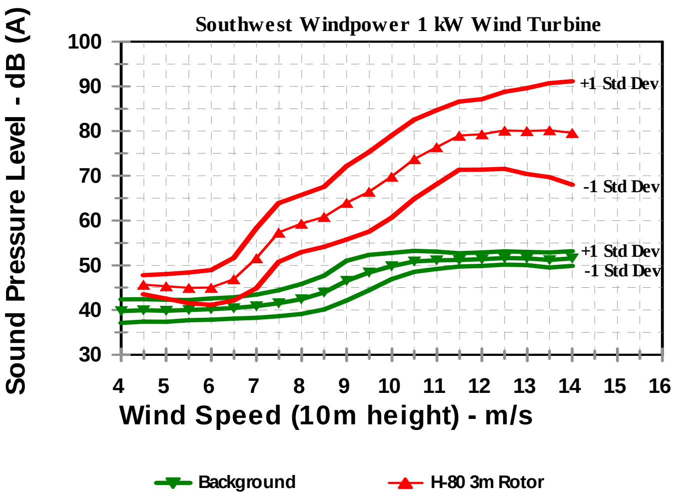

Figure 5. SPL of SWWP H-80 wind turbine with wind speed as independent variable.

Figure 5 shows the "A" weighted SPL of the H-80 wind turbine with Blade #1 compared to background noise when the data were binned in 0.5 m/s wind speed bins. In addition to "A" weighting, the wind turbine SPL was corrected by removing the influence of background noise according to procedure in noise standard. The background noise transitions from a 40 dB level to 52 dB between wind speeds of 7 m/s and 10 m/s due to another wind turbine (the Enertech 40 kW) starting up in this wind speed range. In addition to a noise level greater than 80 dB (objectionable to most people[5]) above a 10 m/s wind speed, this figure also shows the large scatter in the SPL data (the standard deviation is +/- dB above a wind speed of 10 m/s).

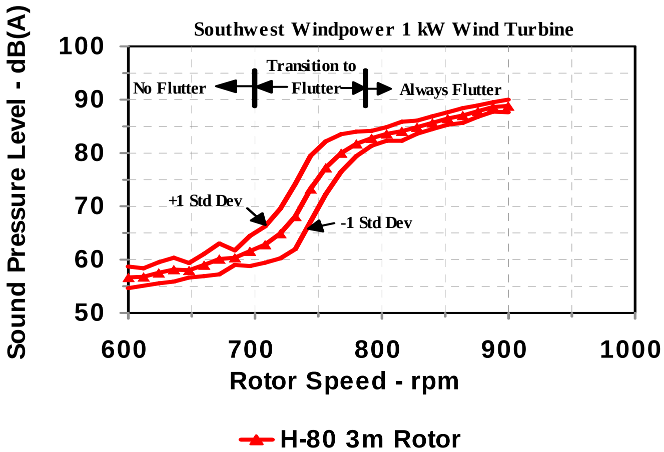

Figure 6. SPL of SWWP H-80 wind turbine with rotor speed as independent variable.

Figure 6 shows the SPL of the same data but binning the data in 12 rpm rotor speed bins instead of 0.5 m/s wind speed bins. In addition to displaying a substantial decrease in data scatter (indicating that noise is more a function of rotor speed than wind speed), from this graph the rotor speed at which the blades begin fluttering and when they are in constant flutter can easily be determined. We had determined this qualitatively by watching electrical frequency display during wind turbine operation, but this graph shows this result quantitatively.

The reduction in data scatter by binning the SPL data with rotor speed instead of wind speed is further demonstrated in Fig. 7 and Fig. 8 for the blades tested on the SWWP H-80 and Whisper 200 1 kW wind turbines. While it appears from Fig. 7 that Blade #2 is quieter than Blade #1, it also appears that Blade #3 is the loudest of the 3 at high wind speeds. From Fig. 8 the scatter in the data is again much less when binned with rotor speed. This graph also helped us realize that the Whisper 200 with Blade #3 was running unloaded part of the time while the H-80 wind turbine never ran unloaded. In a previous paper[3] we speculated that this was probably due to some difference in the permanent magnet alternators (PMA's) between the H-80 and Whisper 200. We have since discovered that there was a modification of the pump controller to improve the helical pump's operation with solar-PV arrays, but that modification obviously resulted in poorer performance of wind powered systems. It now appears the pumping performance can actually be doubled by adding an additional controller operation to the existing controller[6]. This modification also reduced the noise of the wind turbine and protected it and the helical pump (damage occurred to both in prior testing). Unloading the Whisper 200 wind turbine at a high wind speed can allow the tip speed to reach 200 m/s which can lead to blade failure, and high rpm of wind turbine results in high voltage which can damage helical pump motor. It is also obvious from Fig. 8 that complete unloading of the Whisper 200 wind turbine increased SPL significantly.

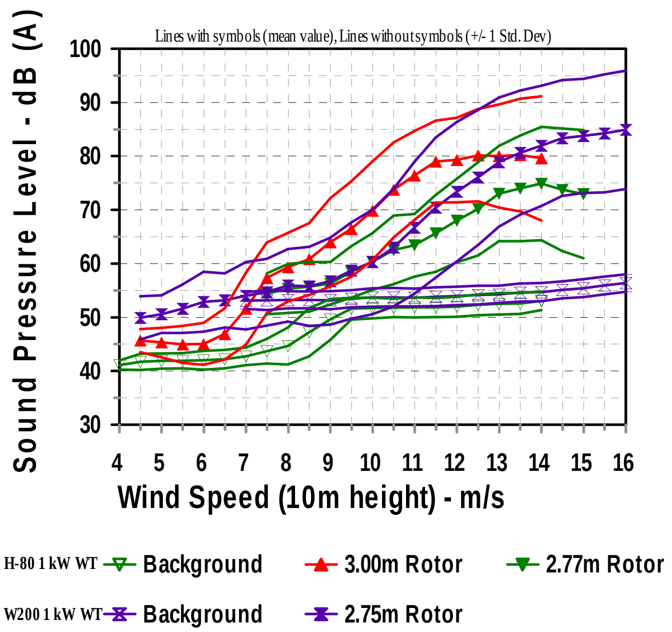

Figure 7. SPL data for 3 blades tested on 1 kW wind turbine with wind speed as independent variable.

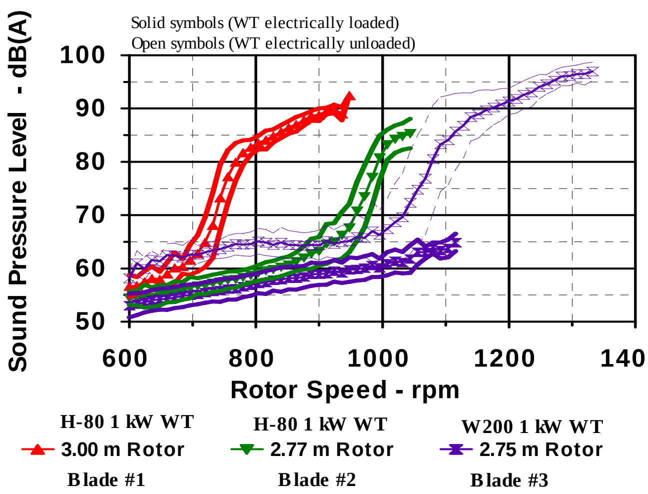

Figure 8. SPL data for 3 blades tested on 1 kW wind turbine with rotor speed as independent variable..

The rotor speed and sound power level of the different blades tested on the 1 kW wind turbine are shown in Fig. 9 and Fig. 10. Viewing Fig. 9, it is surprising to see how high the rotor speed can be, even at low wind speeds, if the wind turbine is unloaded. "Sound pressure level and intensity are properties of a field position. The total strength of a source of sound is characterized by the sound power emitted by the source."[5] The sound power level can be calculated from the SPL and distance from wind turbine hub[1]. The sound power levels were calculated for all of the blades tested on the SWWP H-80 and W200 wind turbines, and the results shown in Fig. 10. Blade #3 is seen as the superior blade in terms of noise emission as long as the wind turbine is electrically loaded.

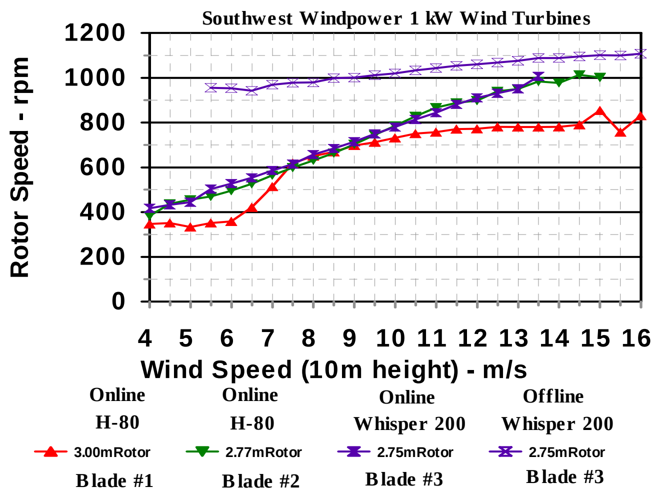

Figure 9. Rotor speed measured for blades tested on 1 kW wind turbine.

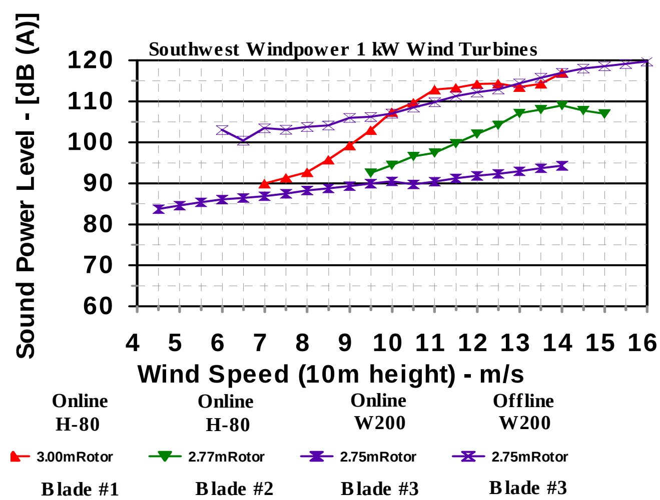

Figure 10. Sound power level calculated from measured SPL for blades tested on 1 kW wind turbine.

B. Bergey Windpower 10 kW Wind Turbine Acoustical Noise Analysis

Figure 11 and Fig. 12 show a comparison of the outboard upper surface (suction side) and the lower surface (pressure side) of the two blades tested (BW03 and SH3055) for noise emission on the Bergey 10 kW PMA water pumping system. An intermediate Bergey 10 kW blade design with the SH3052 airfoil was performance tested at CPRL but we didn't collect any noise data on these blades. However, noise data had been collected on the SH3052 blades previously[2]. Both Bergey blade designs that noise data were collected on, were made using fiber glass pultrusion which is a manufacturing process where strands of fiber glass are pulled through a resin bath to wet them and then are pulled through a template to form them into a specific shape. Pultrusion results in the blade having a constant chord and constant twist distribution, but Bergey Windpower modifies the outboard part of the blade so there is a chord, twist, and airfoil change for this part of the blade. The standard blade design sold by Bergey during the 1990's is shown on the left (the blade with the leading edge pitch weight) in both Fig. 11 and Fig. 12, and the blade on the right in both figures is the most recent Bergey 10 kW blade design – the one they have sold since 2004. The original blade design uses a very thin, highly cambered airfoil (the BW03), while the new blade airfoil is much thicker with some aft camber (the SH3055). Obviously the rotation of the blade rotors is different (clockwise for original blades and counter-clockwise for new blades – w.r.t. observer upwind). Both blades have a chord change on the outboard part of the blade. On the BW03 blade the chord change begins at the pitch weight; the chord is linearly reduced about 30% to create a different airfoil at the tip (this also actually results in some twist being added and leading edge camber being reduced at the tip). However, on the SH3055 blade the chord change is over a much shorter span and the chord tapers from the trailing edge instead of the leading edge. In terms of noise output, a discontinuous change in chord near the tip is good for reducing the noise because it breaks a strong wingtip trailing edge vortex into two smaller trailing edge vortices – one shed at the chord discontinuity and the other at the tip.

Figure 11. Upper surface (suction side) of tested Bergey 10 kW blades.

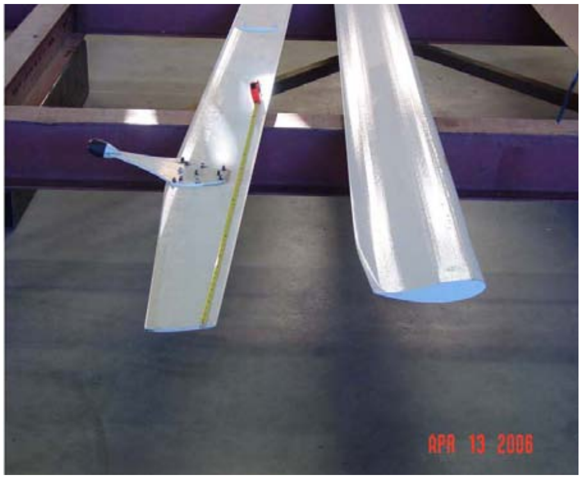

Figure 12. Lower surface (pressure side) of tested Bergey 10 kW blades.

Figure 13 shows the SPL of two different blades tested on the Bergey 10 kW wind turbine with the wind turbine electrically loaded and unloaded. The scatter in the SPL data for the 10 kW wind turbine is significantly less than that for the 1 kW wind turbine (Fig. 7). The SPL of the online data for the two blades were almost the same, but the offline SPL of the new blades with the SH3055 airfoil were quieter than the old style blades with the BW03 airfoil.

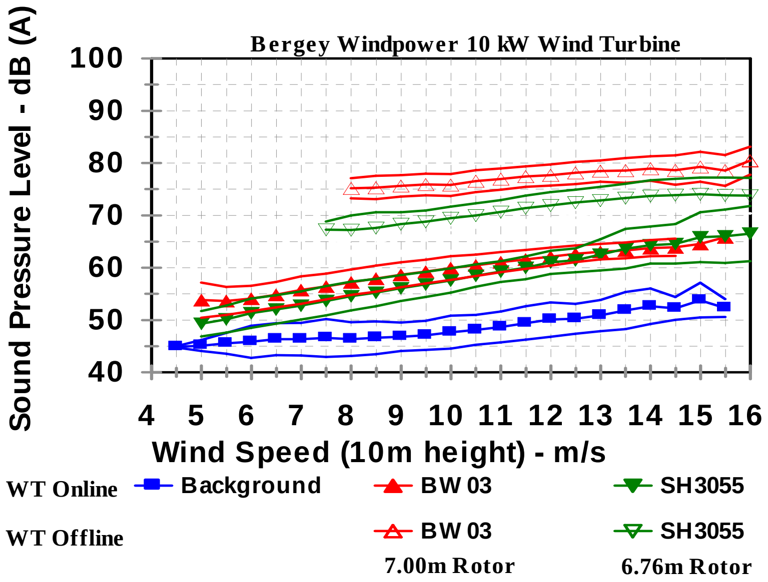

Figure 13. SPL of 2 different blades tested on 10 kW wind turbine with wind speed as independent variable.

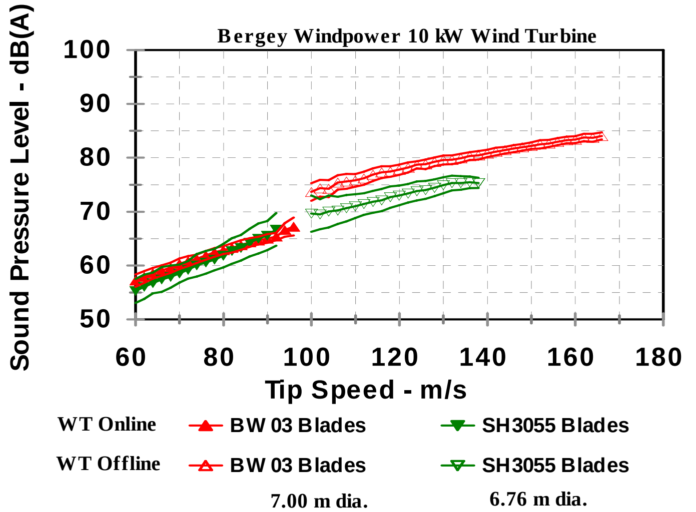

Figure 14. SPL of 2 different blades tested on 10 kW wind turbine with tip speed as independent variable.

Figure 14 shows the SPL data of the two blades tested on the Bergey 10 kW wind turbine when binned by tip speed instead of by wind speed. There is not a significant decrease in data scatter when binned by tip speed rather than wind speed when comparing to Fig. 13. This is different than the blade analysis for the 1 kW wind turbine in which data scatter was significantly decreased by binning the data with rotor speed instead of wind speed (binning with tip speed is approximately equivalent to binning with rotor speed, which will be demonstrated later).

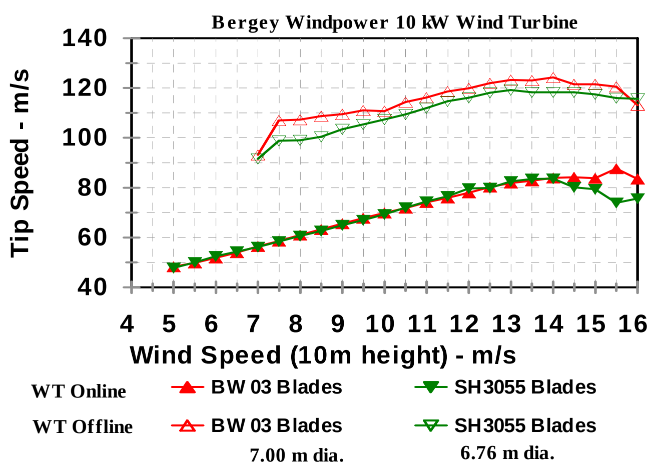

Figure 15. Tip speed for 2 different blades tested on the 10 kW wind turbine.

Figure 15 shows the tip speed variance for the blades tested on the Bergey 10 kW wind turbine. The tip speed is about the same for the online data, but the BW03 blade tip speed was about 5 dB higher for the offline data.

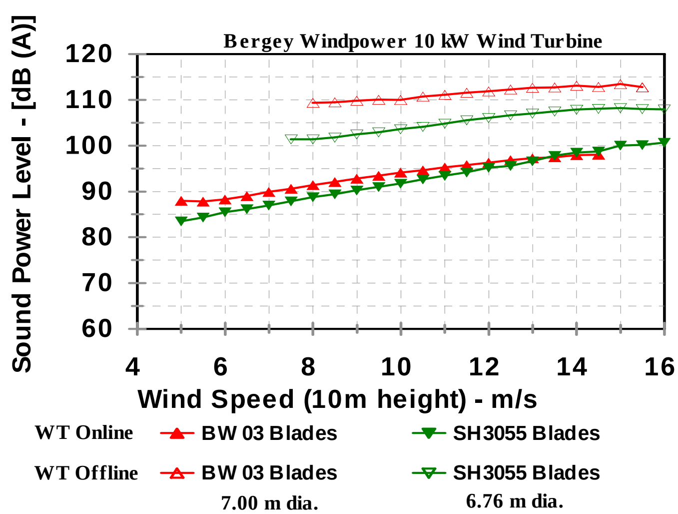

Figure 16. Sound Power Level for 2 different blades tested on the 10 kW wind turbine.

Figure 16 shows that the online sound power levels for the two different blades tested on the Bergey 10 kW wind turbine were about the same, but the offline sound power level for the newer blades was lower than that of the original blades.

C. **Comparison of the SPL of the 1 kW Wind Turbine to that of the 10 kW Wind Turbine**

Figure 17 shows the average acoustical SPL (when binned with wind speed) for all the data collected on the 1 and 10 kW wind turbines (e.g. the standard deviations of each configuration have been omitted for clarity). The open symbols (except for background noise which are always represented as "open square symbols") represent wind turbine noise when there is no electrical loading on the wind turbine, i.e. the turbine is free to spin with only furling to keep it from going into a "run away." Furling was achieved on both upwind turbines (1 kW and 10 kW) due to an offset between the blade rotor axis and the tower axis: at a certain wind speed the thrust on the rotor will turn the power head horizontally out of the wind. The solid symbols represent the wind turbine when there was an electrical load (pump motor) connected to the wind turbine. The highest average SPL occurred for both the 1 and 10 kW wind turbines when there was no electrical load. This was logical since that was when the highest tip speed occurred. At higher wind speeds the online SPL data for the older (H-80) 1 kW wind turbine reached excessive levels because the blades were fluttering. Offline operation occurred on the Whisper 200, but it was due to a modification of the pump controller to improve pumping performance when power was from solar-PV. However, although not shown in this paper, the new pump controller also resulted in better performance of a wind powered system at low wind speeds which is always desirable for a wind powered water pumping system, so this attribute in a new modified controller should be maintained.

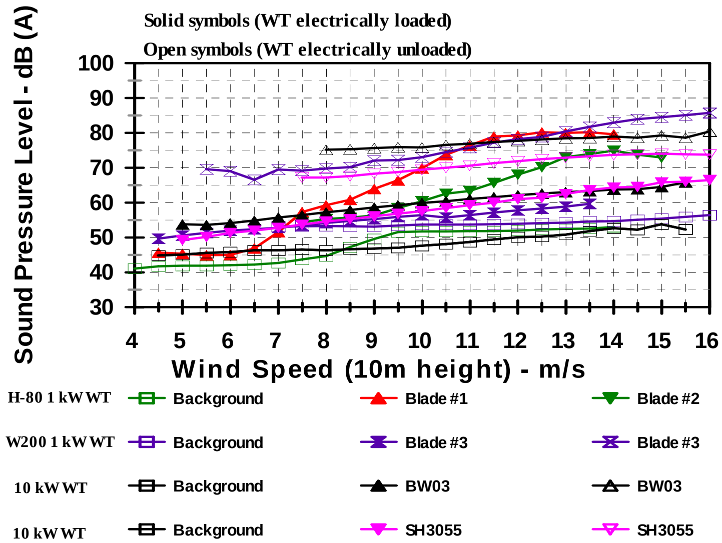

Figure 17. Comparison of SPL for blades tested on 1 and 10 kW wind turbines with wind speed as independent variable.

Figure 18 shows the same data (except no background noise shown) as shown in Fig. 17, but the data were binned in terms of tip speed instead of wind speed. For the 1 kW data it is obvious when the transition to flutter is occurring and when the wind turbine rotor is always fluttering. The offline data on the 1 kW Whisper 200 wind turbine with Blade #3 almost reaches 100 dB, but the blades tested on the 1 kW H-80 may have reached this level also if the controller disconnected the pump motor load from the wind turbine. We actually had 3 blades break off from the Whisper 200 wind turbine during a thunderstorm in July 2006 when the wind turbine was unloaded by the pump controller. In this instance, the pump controller disconnected the wind turbine from the pump to prevent the high voltage from damaging the pump. The voltage can be set lower on the SWWP Whisper 200 which we have done, but unless modification of existing pump controller or another controller is used, then wind turbine

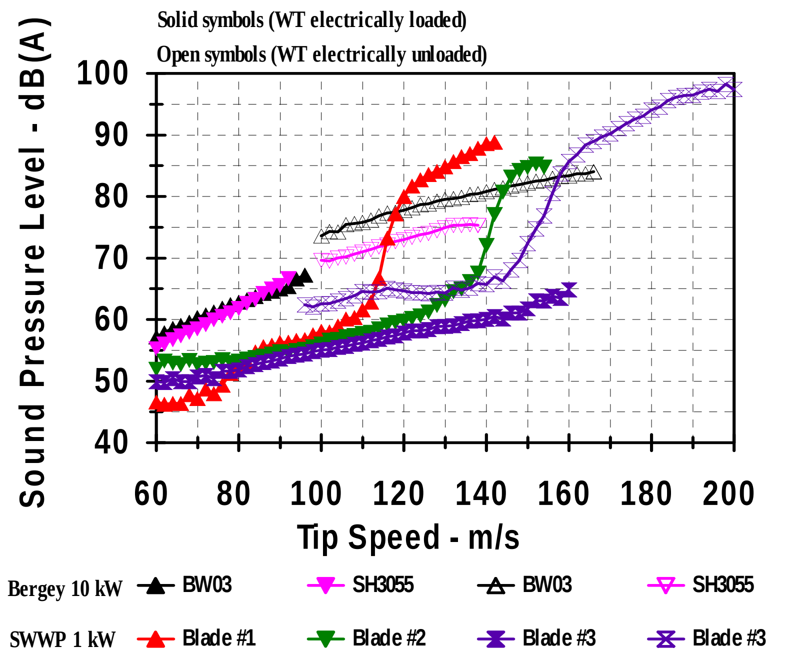

Figure 18. Comparison of SPL for blades tested on 1 and 10 kW wind turbines with tip speed as independent variable.

failure is still possible on this system. The results shown for the average SPL binned with tip speed on the 10 kW wind turbine is similar to the data binned with respect to wind speed (online SPL for the two blades about the same and offline SPL for the new blades lower than that of original blades). The offline data of the new blades on the Bergey 10 kW wind turbine stops at a tip speed of 140 m/s, but this was due to a malfunction of the electrical frequency transducer. We believe these data could probably be linearly extrapolated beyond 140 m/s tip speed to a 170 m/s tip speed. In Fig. 17 the online SPL data for the SWWP and Bergey wind turbine are seen to be quite similar. In contrast, in Fig. 18 the Bergey SPL data are well above the SWWP data at low tip speeds.

The explanation for the disparity between the online data for the two wind turbines in Fig. 17 and Fig. 18 can be seen in Fig. 19. Figure 19 shows the average wind speed measured for all the data shown in Fig. 18, with tip speed as independent variable. The average wind speed of the Bergey wind turbine at a tip speed of 60 m/s is 8.5 m/s, but the average wind speed of Blade #3 on Whisper 200 was only 7 m/s. The average wind speed for Blade #3 on Whisper 200 doesn't reach 8.5 m/s until a tip speed of 95 m/s is reached, and according to Fig. 18, at this tip speed the SPL is only a few dB less than the Bergey wind turbine blade data. Another observation from Fig. 19 is that the average wind speed does not always increase with tip speed (note offline data for Blade #3 on SWWP 1 kW wind turbine), and this is due to wind turbine furling and slowing down in high winds. This phenomenon obviously is a contributor to the increase in SPL data standard deviation when wind speed is the independent variable.

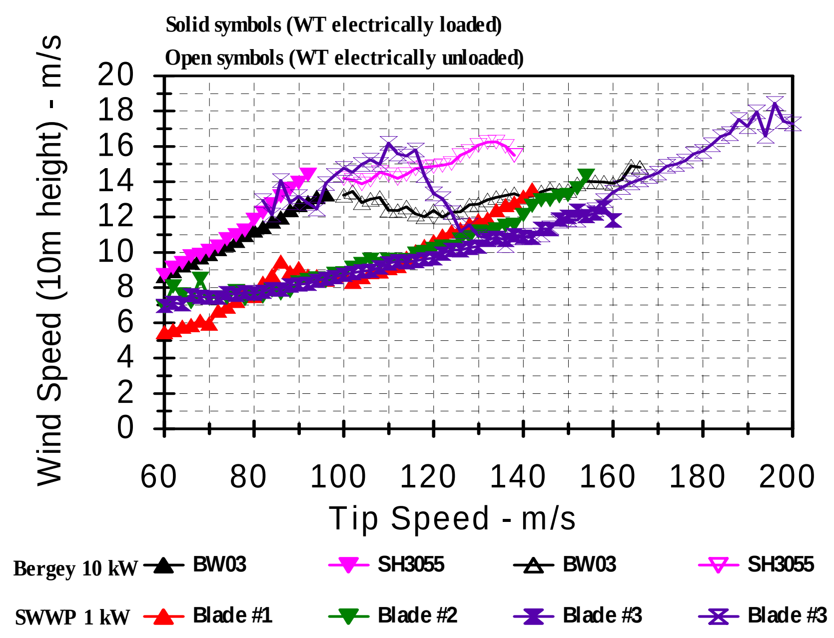

Figure 19. Comparison of wind speed for blades tested on 1 and 10 kW wind turbines with tip speed as independent variable.

III. Conclusions

Of the two wind turbines (Southwest Windpower 1 kW and Bergey Windpower 10 kW) which were analyzed for sound pressure level (SPL) in this paper, use of either rotor or tip speed as the independent variable (as opposed to wind speed) definitely improved the analysis of the 1 kW wind turbine the most. For the small wind turbines analyzed in this paper the majority of the noise was produced by the blade rotor, so it is not surprising that the data scatter was reduced significantly when the SPL data were binned in terms of rotor or tip speed. For the 1 kW wind turbine, binning the data with rotor speed enabled one to see when flutter of the blades began occurring which could lead to proper application of an additional load by the pump controller to: (1) keep the noise low, (2) improve the pumping performance, and (3) protect the wind turbine and pump motor. It is obvious from Fig. 8 (SPL vs. Tip Speed) that each blade modification on the 1 kW wind turbine was an improvement in decreasing the amount of blade flutter although this conclusion is not obvious from Fig. 7 (SPL vs. Wind Speed). The SPL results obtained for the 10 kW wind turbine were similar whether binned with wind speed or with tip speed, but binning with tip speed does allow one to see just how loud the wind turbine was – the highest tip speed was always the highest SPL.

On the other hand, when wind turbines furl the rotor speed will usually decrease, so the noise will sometimes decrease at higher wind speeds. Recording SPL as a function of tip speed is a good way of determining at what tip speed the wind turbine begins to flutter and to determine whether modifications to the blade are improving flutter (and thus reducing noise levels). According to the online data presented in Fig. 18, the SH3055 airfoil blade produces more noise than the Wortmann FX 63-137 airfoil blade. These airfoils were tested for noise in a wind tunnel[7], and the noise generated by the two airfoils appeared to be about the same, but the wind speed was only 32 m/s. Future wind tunnel airfoil noise tests should be at much higher wind speeds.

Acknowledgments

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