AFFECT OF NEW BLADES ON NOISE REDUCTION OF SMALL WIND TURBINE WATER PUMPING SYSTEMS

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ABSTRACT

Acoustical noise data were collected on small wind turbines used for water pumping -- different blade designs were tested on each wind turbine. Three different blade designs were tested on 1 kW wind turbines and each successive blade design was shown to produce less noise with respect to rotor speed. All three blade designs, however, produced acoustical noise above 80 dB during part of their operation due to wind turbine blade fluttering which occurred when a specific rpm was exceeded for each blade design. Two radically different blade designs were tested on a 10 kW wind turbine. For the loaded condition (online) the average acoustical noise measured for both blade designs was within a few dB of each other (noise under 70dB), but for the unloaded condition the average acoustical noise measured for the newer blade design was 4 to 8 dB less. The acoustical noise for both blade designs of the 10 kW wind turbine usually ranged between 70 and 80 dB in the offline condition, but occasionally exceeded 80 dB. Binning the measured sound data in terms of rotor or tip speed instead of wind speed greatly reduced the scatter in the data and enabled better evaluation of the noise emission for the different blade designs. A recommendation for obtaining an acceptable noise emission from a small stand-alone wind turbine can be found in the conclusions.

INTRODUCTION

The acoustical noise produced by most utility scale wind turbines is not regarded by most people as excessively loud (as long as not in a runaway condition). However, the noise emitted from small wind turbines does not have such a stellar reputation. Small wind turbines are mainly used in stand-alone applications like battery charging or water pumping (not grid-tied like the utility scale wind turbines), so they sometimes operate in an unloaded condition. For instance, the controller will unload the turbine to keep batteries from being over charged or to keep a submersible pump motor from being damaged). Although adding a dump load to prevent unloaded conditions at high wind speeds could alleviate this situation, this may not a viable option since the wind turbine permanent magnet alternator (PMA) could be operating above rated power by supplying electricity to both the pump motor and the dump load and therefore could be damaged. To address this noise problem, small wind turbine companies have been designing new blades in attempts to decrease the acoustical noise produced in high winds. This paper documents some of their progress.

There have been many publications about noise emission from wind turbines since the late 70's. Wagner (Wagner, 1996) has even written a book which specifically addresses wind turbine noise. Paul Gipe was one of the first to begin bringing attention to the perceived excessive noise produced by small wind turbines by collecting noise data for small wind turbines and publishing the data on his website (Gipe, 2000). The National Renewable Energy Laboratory (NREL), National Wind Test Center near Boulder, CO has been conducting research on noise produced by small wind turbines for the past six years (Migliore, 2003). Acoustical noise emission data were collected in a low speed wind tunnel on six airfoils used on small wind turbines (Selig, 2004 and Migliore, 2004). Two of the airfoils (Wortmann FX63-137 and Selig-Hanley SH3055) tested in the wind tunnel were used on the blades that are the subject of this paper. Some acoustical noise emission testing on the 1 kW wind turbine used for this paper was also reported in a previous paper (Vick, 2005).

Test Setup, Instrumentation and Data Acquisition

The Southwest Wind Power[1] 1 kW H-80 and Whisper 200 wind turbines were installed on a 19.5 m (63 ft) tilt-up guyed pipe tower. Pumping performance data collection on the H-80 wind turbine began in Nov., 2003 and noise data collection began in Mar., 2005. Pumping performance data collection on the Whisper 200 wind turbine began in Aug., 2005 and noise data collection began in Nov., 2005. The H-80 and Whisper 200 wind turbines output variable voltage/variable frequency 3-phase AC electricity that is rectified to DC in a model IO102 Grundfos[1] control box before it is connected to a DC motor and helical pump. The main controller for this Grundfos pump is located in the motor casing of the DC Motor in the well (or, in our case, a sump), but there is an additional CU200 controller above ground between this controller and the rectifier. This additional controller informs the operator of faults and also allows the operator to manually connect or disconnect the wind turbine from the pump motor. There is also a switch on the IO102 box that allows the operator to brake the wind turbine in low winds (e.g. shorts all three phases). The differences between the H-80 and Whisper 200 turbines were:

1. a different type and higher quality set of slip rings
2. used four instead of two bearings to distribute the loads evenly and prevent shaft and bearing failures
3. redesigned tail pivot bushing
4. redesigned yaw bearing.

The Bergey[1] 10 kW wind turbine was installed on an 18.5 m (60 ft) guyed lattice tower and pumping performance data collection began in 1988 and noise data collection began in Apr., 2006. The Bergey 10 kW wind turbine also outputs variable voltage/variable frequency 3-phase AC electricity, but it is connected through a Bergey pump controller to a 60 Hz 3.8 kW 230 V 3-phase submersible motor that drives a 3.8 kW 15-stage centrifugal pump. Capacitance is connected in parallel with the motor. Bergey discontinued selling the 10 kW water pumping units in 2000 and Grundfos as of this year is not selling the wind powered helical pump units due to poor performance of Whisper 200 wind turbine connected to their pump.

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[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA – Agricultural Research Service.

The hub height wind speed for all wind turbines was measured with Met-One[1] Model 014 cup anemometers. The wind turbine power produced by the wind turbines was measured with Flex-Core[1] Model P-144X5 Power Transducers. The water flow rate was measured with Hersey[1] Models 30A and 165 transducers (for the 1 kW and 10 kW wind turbine water pumping systems, respectively). The water pressure was measured with a Honeywell[1] Model EA transducer. The pressure is important to determine the equivalent pumping depth - different pumping depths from 0 to 150 m can be simulated using a back pressure valve. The electrical frequency of all wind turbines was measured with a transducer designed by US Department of Agriculture (USDA) and West Texas A&M University (WTAMU) personnel. The rotor speed was calculated from this frequency with the following equation:

$$RPM = 120 * frequency/ (\# \text{ of PMA poles}) \tag{1}$$

The noise standard used as a basis for the noise data gathered for this paper was IEC 61400-11 (IEC, 2002). This standard recommends estimating the wind speed from the wind turbine power. However, since the unloaded condition was seen as an important case (because the loudest noise emission usually occurs in this condition), the secondary recommendation for determining the wind speed (record wind speed with an anemometer located 2-4 rotor diameters upwind of the wind turbine) was used. We used a RM Young[1] Model 81000 ultrasonic anemometer mounted at a 10 meter height on a portable tilt-up lattice tower to measure wind speed. This anemometer also recorded wind direction, so a separate wind direction sensor was not required. We used a Larson-Davis[1] Model 824 Type 1 sound level meter (SLM). The 1.25 cm (0.5 in) diameter microphone (Model 2541) and low noise microphone preamplifier (PRM902) used were also from Larson-Davis. The SLM and microphone were calibrated at 94 dB with a Larson-Davis model CAL200 calibrator. All noise data were collected using an “A” weighting. Although the IEC 61400-11 recommends a half-spherical open cell foam wind screen of 90 mm (3.5 in) diameter, we instead used one of 180 mm (7 in) diameter since that was the size of primary wind screen used at NREL for high wind speeds. Noise data were collected on 5/23/2006 for both size wind screens, and the difference in sound level was 1 dB or less (as shown in Fig. 1).

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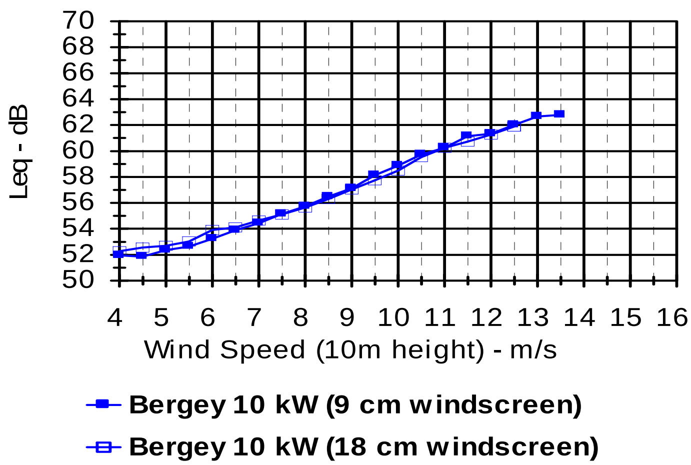

Fig. 1. Effect of Primary Hemispherical Windscreen Diameter on Sound Pressure Level.

The IEC noise standard also recommends the use of a secondary hemispherical wind screen (at least 45 cm in diameter, 13 to 25 mm thick, and 4 to 8 pores per 10mm) for high wind speed measurements. USDA/WTAMU personnel constructed a secondary wind screen that meets these specifications. Noise data were collected for all the wind turbines, with approximately half the data collected with a primary 18 cm hemispherical wind screen and the other half with both 18 cm and 61 cm diameter hemispherical wind screens. Most of the data shown in this report were obtained with both wind screens in place, since the highest noise emission occurred in high winds. If adjacent wind turbines appeared to be affecting the noise being measured for a particular wind turbine at wind speeds above 7 m/s, the operation of those wind turbines were curtailed. The IEC noise standard also recommends the data be averaged every minute. NREL (Migliore, 2003) averaged their data every 10 seconds “To better reflect the dynamics of the turbine”. We decided to average all the data collected during noise data collection every second (the shorter time interval should definitely decrease scatter in the data). All the data, except the sound pressure level (SPL) data, were recorded on a Campbell 23x data logger. The SPL data were recorded on the Larson Davis SLM. The internal clocks of the Campbell 23x data logger and Larson Davis SLM were synchronized to a Casio[1] G-shock 200M DW5600E1V watch (accuracy +/- 1 sec/day) before noise data were collected.

Southwest Windpower H-80/Whisper 200 Blade Designs

Figures 2 and 3 show the blades tested on the 1 kW wind turbines. The airfoil used for all 3 blades was the Wortmann FX 63-137. The blade chord and twist distributions vary with span. Blades #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. 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 it was not possible to determine if tip shape affected noise, since there were other size or weight differences between the blades.

Fig. 2. SWP Blades Tested.

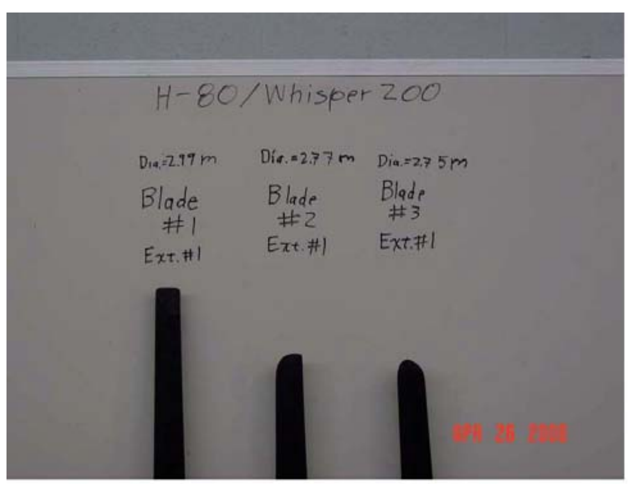

Fig. 3 Difference in SWP Blade Tip Shape.

H-80/Whisper 200 Electrical Loading and Pumping Performance

Although this paper is about the affect of blades on acoustical noise emission, it is also important to know what electrical loading occurred on the different blades tested. Unfortunately, not enough pumping performance data was gathered at a single pumping depth to compare all three blades, so Blade #1 and Blade #2 will be compared at a 100 meter (328 ft) pumping depth and Blade #1 and Blade #3 will be compared at a 75 meter (246 ft) pumping depth. Only data obtained when the wind was coming from the south was used in the performance analysis, since buildings and trees located to the north were felt to cause too much turbulence. The AC power in this paper was corrected to sea level standard day (SLSD). The air temperature and pressure were used to calculate the air density and then the following equation was used to correct the wind speed:

$$WS_{corr} = WS * (\rho_{calc}/\rho_{SLSD})^{1/3} \qquad (2)$$

Where WS_{corr} is corrected Wind Speed for SLSD conditions;
WS is measured Wind Speed;
ρ_{SLSD} is air density at SLSD conditions (1.2255 kg/m^3);
ρ_{calc} is calculated air density (kg/m^3).

The data were then binned in 0.5 m/s bins.

There is still some controversy (Vick, 2005) whether this is the best way to correct power to sea level conditions for small furling wind turbines, so power curves were compared for the same month but different years (the air density correction was about the same). Fig. 4 indicates the AC power generated by Blade #1 is nearly the same as that generated by Blade #2. According to Fig. 5, however, the flow rate measured for Blade #2 was less than that measured for Blade #1. This drop in flow rate was due to a drop in the helical pump performance; this was verified later when the pump was connected directly to utility electricity. This helical pump and motor was shipped to Grundfos, but we have not been informed as to what caused the performance degradation. Despite the pump degradation, what should be noticed in Fig. 4 and 5 is that the wind turbine was electrically loaded by the pump motor almost all the time (e.g. essentially no offline or unloaded data). We should also mention that flow rate was binned in wind speed bins without the wind speed correction above.

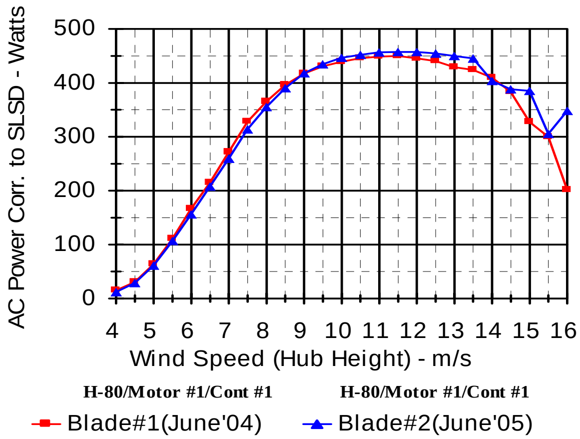

Fig. 4. Power Curves for SWP Blades 1 & 2. at 100m head (Bushland,TX).

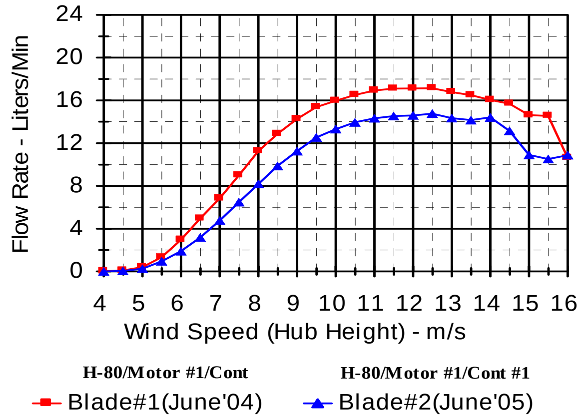

Fig. 5. Flow Rates for SWP Blades 1 & 2. at 100m head (Bushland,TX).

Fig. 6 shows the power output from Blade #1 with the H-80 wind turbine and Blade #3 with the Whisper 200 wind turbine – both connected to the same motor, pump, rectifier, and controllers. Now we see a power reduction between Blade #1 and Blade #3. This is likely due to the changes between the H-80 and the Whisper 200 PMA, since there is not much difference between Blade #2 and Blade #3. More important than the drop in power at wind speeds below 10 m/s is that the Whisper 200 wind turbine was running unloaded a large percentage of the time above a wind speed of 10 m/s (this is also likely due to the differences between the two PMA's). Fig. 7 also indicates that the flow rate dropped for Blade #3 with the Whisper 200 PMA – the drop is of greater magnitude than the power drop due to the previously mentioned further degradation in the motor/helical pump. The helical pump/motor on our solar-PV system has not shown this degradation and both these identical helical pumps (Model 6 SQF-2) were installed at about the same time (Wind system – Nov/2003, Solar system – Feb/2004).

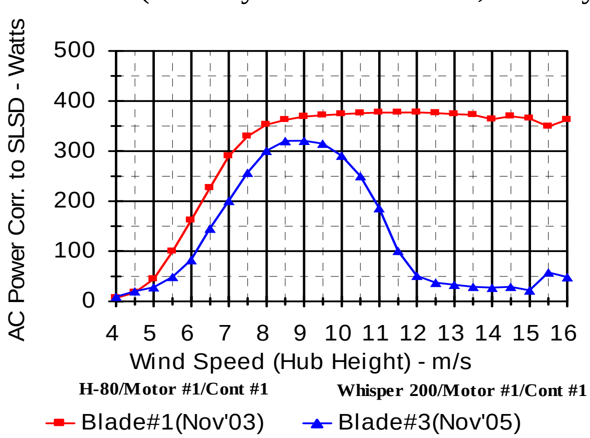

Fig. 6. Power Curves of SWP Blades 1 & 3 at 75m head (Bushland,TX).

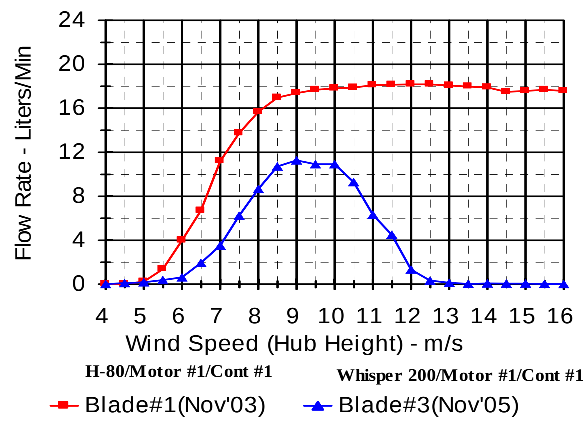

Fig. 7. Flow Rates of SWP Blades 1 & 3 at 75m head (Bushland,TX).

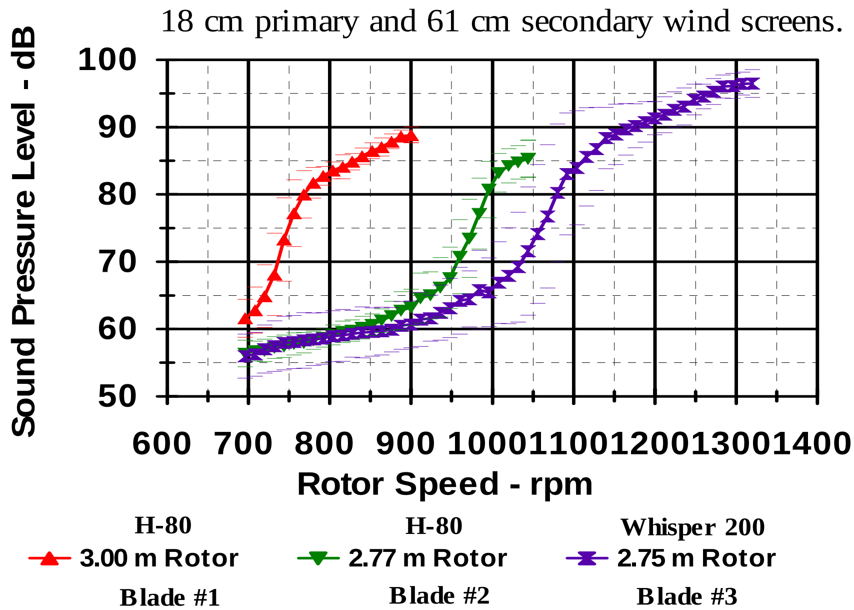

Fig. 8. Effect of SWP Blades on SPL (Bushland, TX).

Noise Analysis of Blades Tested on H-80/Whisper 200

It is evident from Fig. 8 that Southwest Wind Power decreased the noise output for each successive blade design in terms of rotor speed. The rapid increase in noise is due to blade flutter. Blade #2 flutter occurred at a much higher rotor speed than Blade #1 flutter, due probably to its shortened length. There was delay in the rotor speed at which flutter occurred from Blade #2 to Blade #3, due probably to the increased stiffness of Blade #3. The tip shape also changed between all three blades, but we feel this was less of an affect. The error bars for each curve represent +/- one standard deviation. For Blade #1 and Blade #2 the standard deviation is relatively small, but that of Blade #3 is much larger, due to the wind turbine running offline more of the time. Note that, if the rotor speed was limited to a certain maximum rpm (for instance by adding an additional electrical load) then the noise could be suppressed below 70 dB at all wind speeds. Since this wind turbine is under loaded then damage of PMA is unlikely with the addition of a dump load.

Fig. 9 shows how the rotor speed increased for Blade #2 compared to Blade #1; this increase in rpm is due to the shorter diameter of Blade #2. Note that the rotor speed of Blade #3 is higher than that for Blade #2 at higher wind speeds due to the Blade #3 configuration running offline more often (compare Fig. 4 with Fig. 6) because Blade #3 is installed on the Whisper 200 PMA instead of the H-80 PMA.

Fig. 10 shows the background noise and the noise measured for all three blades tested on the H-80/Whisper 200 wind turbines for different wind speeds. The noise for all three blade configurations was corrected for the influence of background noise using the following equation from IEC 61400-11:

$$L_s = 10 * lg [10^{(0.1*Ls+n)} – 10^{(0.1*Ln)}] \quad (3)$$

Where L_s is the equivalent continuous sound pressure level, in dB, of the wind turbine operating alone;

L_{s+n} is the equivalent continuous sound pressure level, in dB, of the wind turbine plus background noise;

L_n is the background continuous sound pressure level, in dB.

Blade #1 (mounted on the H-80 PMA) had the highest SPL for the wind speed range of 7 to 13 m/s, but the SPL for Blade #3 (mounted on the Whisper 200 PMA) was as high as Blade #1 for wind speeds above 13 m/s. The SPL for Blade #2 (mounted on the H-80 PMA) was the same as that for Blade #3 for wind speeds below 10.5 m/s, but remained lower than that for Blade #3 above that wind speed. We feel that the noise measured for Blade #3 when compared to Blades #1 and #2 is different when binned to wind speed instead of rotor speed because, as discussed before, Blade #3 with the Whisper 200 PMA was running unloaded (and therefore, at high rpm) at these wind speeds. According to Fig. 8, Blade #3 should be the quieter blade for any one particular wind turbine, and we feel it will be if the Whisper 200 is modified so it doesn't spend

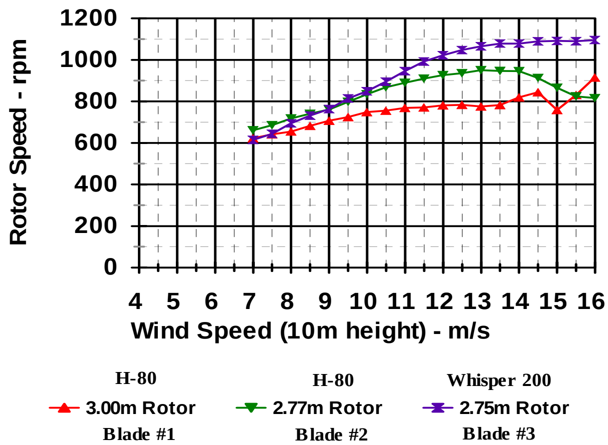

Fig. 9. Effect of Blades and Wind Turbine on Rotor Speed (75m head, Bushland,TX).

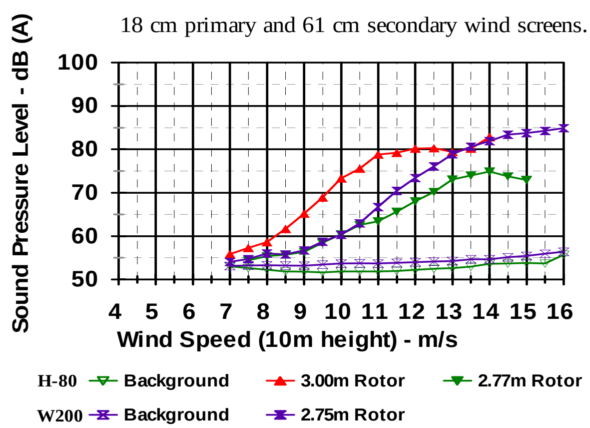

Fig. 10. Effect of Blades and Wind Turbine on SPL (75m head, Bushland, TX).

so much time running offline at the higher wind speeds.. Another problem which appears to have aggravated the situation is the controller in the helical pump motor was changed in order for it to run more efficiently with solar-PV modules. This change occurred in 2004 but this new controller motor wasn't tested until Jan, 2006 – no performance or noise data is shown in this paper since this helical pump motor was tested. However, Grundfos has redesigned that controller again and with some modifications of the Whisper 200 PMA voltage output, a solution may yet be found for this wind turbine water pumping system.

<u>Bergey Windpower 10 kW Blade Designs</u>

Fig. 11 shows a comparison of the outboard upper surface (suction side) of the two blades tested 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 USDA but no noise data was collected on this configuration). Both blade designs were made using fiber glass pultrusion.

Pultrusion 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 90's is shown on the left (the one with the leading edge pitch weight), and the one on the right is the most recent Bergey 10 kW blade design -- having been 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). 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.

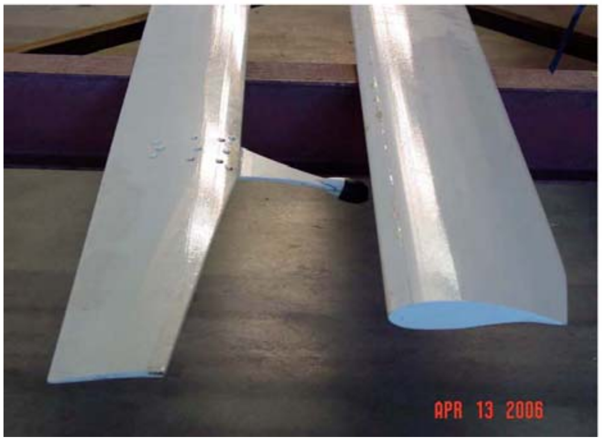

Fig. 11. Upper Surface (Suction Side) of Bergey 10 kW Blades Tested.

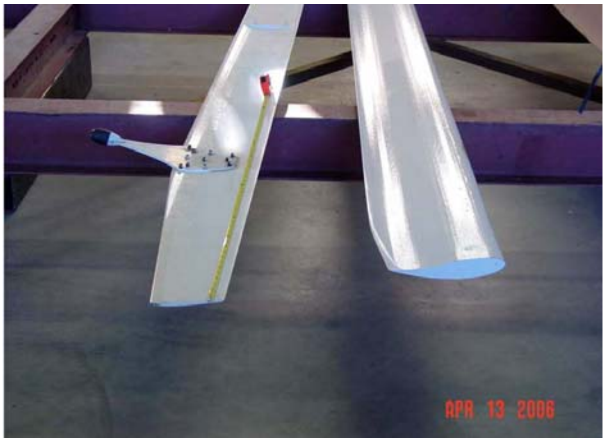

Fig. 12. Lower Surface (Pressure Side) of Bergey 10 kW Blades Tested.

Fig. 12 shows the outboard lower surface (pressure side) of the BW03 and SH3055 blades. Both blades have a beveled trailing edge, although the beveled trailing edge extends for 1.22 m (4 ft) on the BW03 blade while the SH3055 blade beveled trailing edge extends for about 0.6 m (2 ft). The beveling makes the trailing edge sharp which is also considered good for reducing noise. Another obvious design difference is the BW03 blades were designed to rotate clockwise (viewed by an observer upwind of the wind turbine) and the SH3055 blades were designed to rotate counter-clockwise. The BW03 blade rotor is 7 meters in diameter and the SH 3055 blade rotor is 6.76 meters in diameter.

Bergey Windpower 10 kW Electrical Loading and Pumping Performance Analysis

Field testing on the SH3055 blades at Bushland, TX was performed from Apr. '05 to May '06. After collecting noise data on the SH3055 blades, the Bergey PMA unfortunately shorted out due to a controller logic error. The PMA used to replace the shorted out PMA had a different stator winding. Noise data were gathered on the BW03 blades when the new PMA was installed. As can be seen in Fig. 13, the power curve for the BW03 blades in May '04 was very close to that measured in May '06 except for wind speed range of 9.5 to 13 m/s. The power curve of the SH3055 blades (May '05) was better than the BW03 blades (May '04) up to 10 m/s and in the wind speed range of 10 to 12.5 m/s they were similar. However, above a wind speed of 12.5 m/s the BW03 blades were online at least part of the time (AC power above 0.5 kW and flow rate above 10 liter/min) while the SH3055 blades stayed offline most of the time. All the corresponding months of the year also showed a similar trend at these high wind speeds. Fig. 15 shows the total number of samples (minutes) gathered in each of these data sets and the percentage of time they were offline. The SH3055 blades show an earlier cut-in and slightly improved production at wind speeds below 10 m/s, but more difficulty staying online at higher wind speeds compared to the BW03 blades.

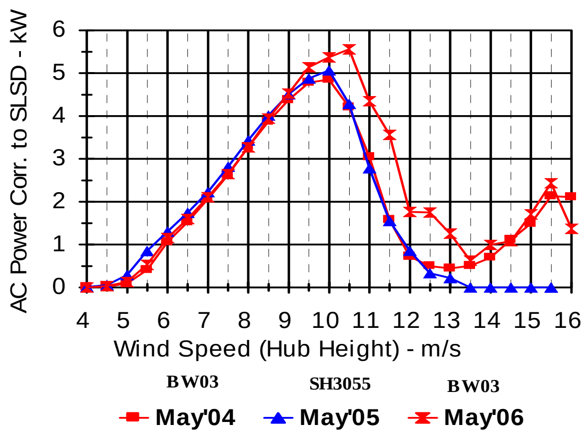

Fig. 13. Power Curves of Bergey 10 kW Blades at 75m head (Bushland, TX).

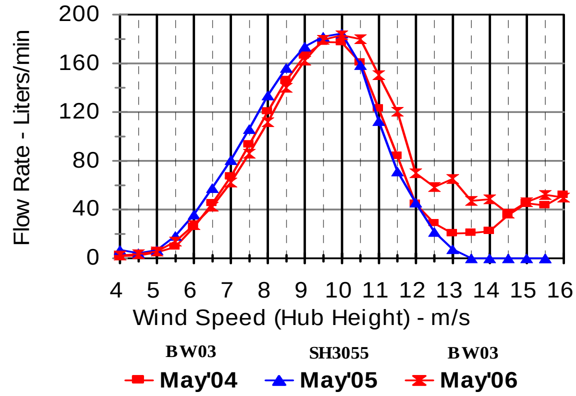

Fig. 14. Flow Rates of Bergey 10 kW Blades at 75m head (Bushland, TX).

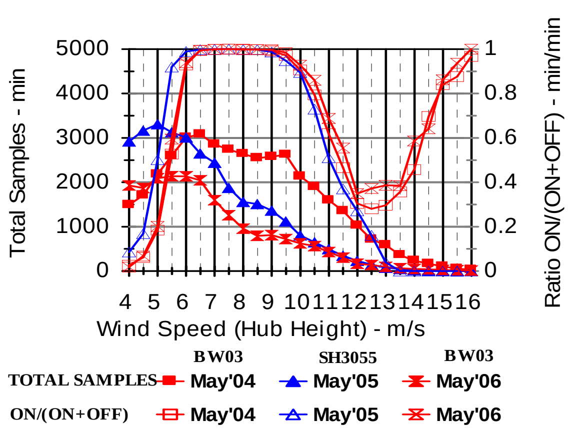

Fig. 15. Number of Samples and Percentage of Time "ON" for Bergey 10 kW Blade Testing.

<u>Bergey Windpower 10 kW Noise Analysis</u>

The average rotor speed during the noise data collection is shown in Fig. 16. The data were separated into online and offline, since the rotor speed is so different. The online data shows the SH3055 blades operated just a little faster than the BW03 blades. The rotor speed of the offline data was almost identical for the two blades.

Fig. 17 shows the sound pressure level of the noise data collected on the Bergey 10 kW. For the online condition, the SH3055 blades were a little quieter than the BW03 blades for wind speeds below 12 m/s, even though they were actually spinning faster than the BW03 blades. The SPL was about the same for the two blades for higher wind speeds. For the offline condition, the SH3055 blades were anywhere from 4 to 8 dB quieter than the BW03 blades.

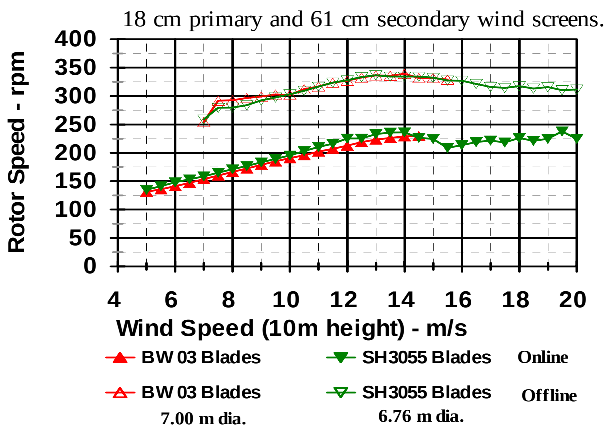

Fig. 16. Rotor Speed of Bergey 10 kW Testing (Primary & Secondary Windscreen).

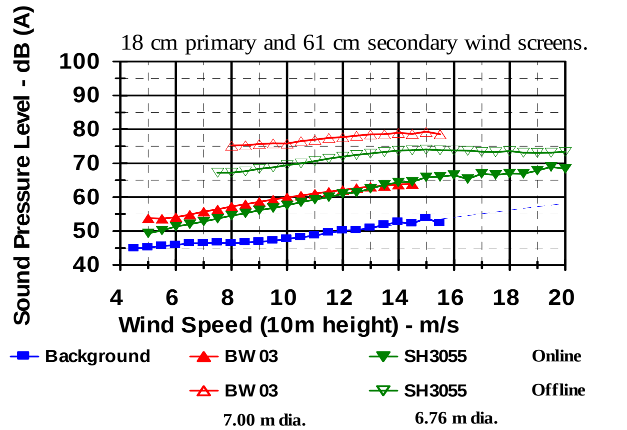

Fig. 17. SPL of Bergey 10 kW Testing (Primary & Secondary Windscreen).

All of the SPL data shown so far in this paper were obtained with two wind screens – an 18 cm (7 in) diameter primary and a 61 cm (24 in) diameter secondary wind screen. We acquired SPL data with only the primary wind screen (on the same day as we acquired the data shown in Fig. 16 and 17) to determine the effect of the secondary wind screen. Fig. 18 shows the rotor speed, and the main difference from Fig. 16 is the SH3055 blade was spinning faster than the BW03 Blade in the unloaded condition. The SPL measured with just the primary wind screen is shown in Fig. 19. The difference in SPL is still small for the online condition, but the SPL difference is not as big for the offline condition; this is probably due to the higher SH3055 blade rotor speed, compared to that in Fig. 16.

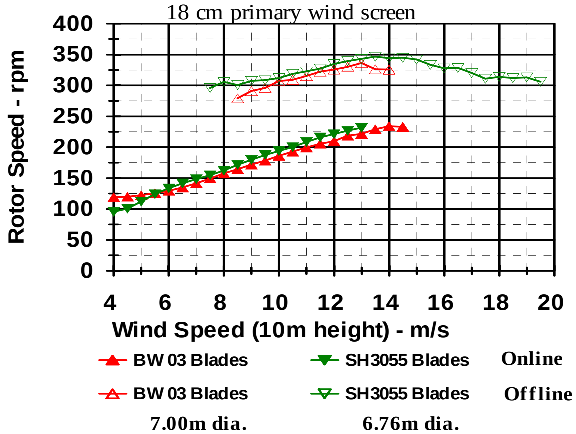

Fig. 18. Rotor Speed of Bergey 10 kW Testing (Only Primary Windscreen).

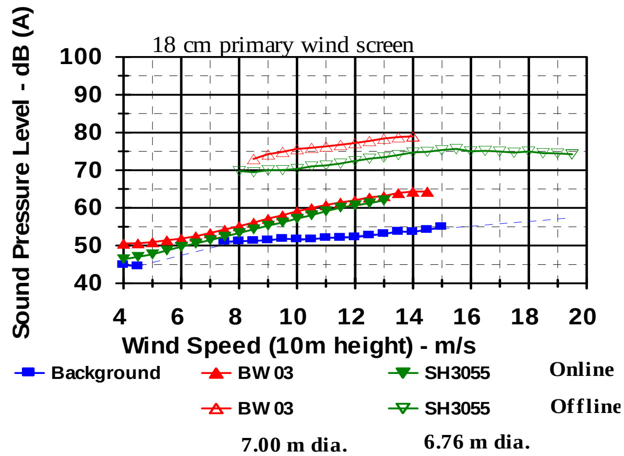

Fig. 19. SPL of Bergey 10 kW Testing (Only Primary Windscreen).

<u>Noise Analysis in Terms of Tip Speed</u>

Fig 20 shows the sound pressure level of the Southwest Windpower 1 kW wind turbine and the Bergey Windpower 10 kW wind turbine as a function of tip speed. Solid symbols represent online data and open symbols represent offline data. While the Southwest Windpower blades were quieter than the Bergey Windpower blades for tip speeds below 110 m/s, once the Southwest Windpower blades began fluttering, their SPL would exceed the SPL of the Bergey blades. Southwest Windpower Blade #3 on the Whisper 200 PMA ran offline most of the time at higher wind speeds and resulted in a tip speed of almost 200 m/s with a SPL of 97 dB.

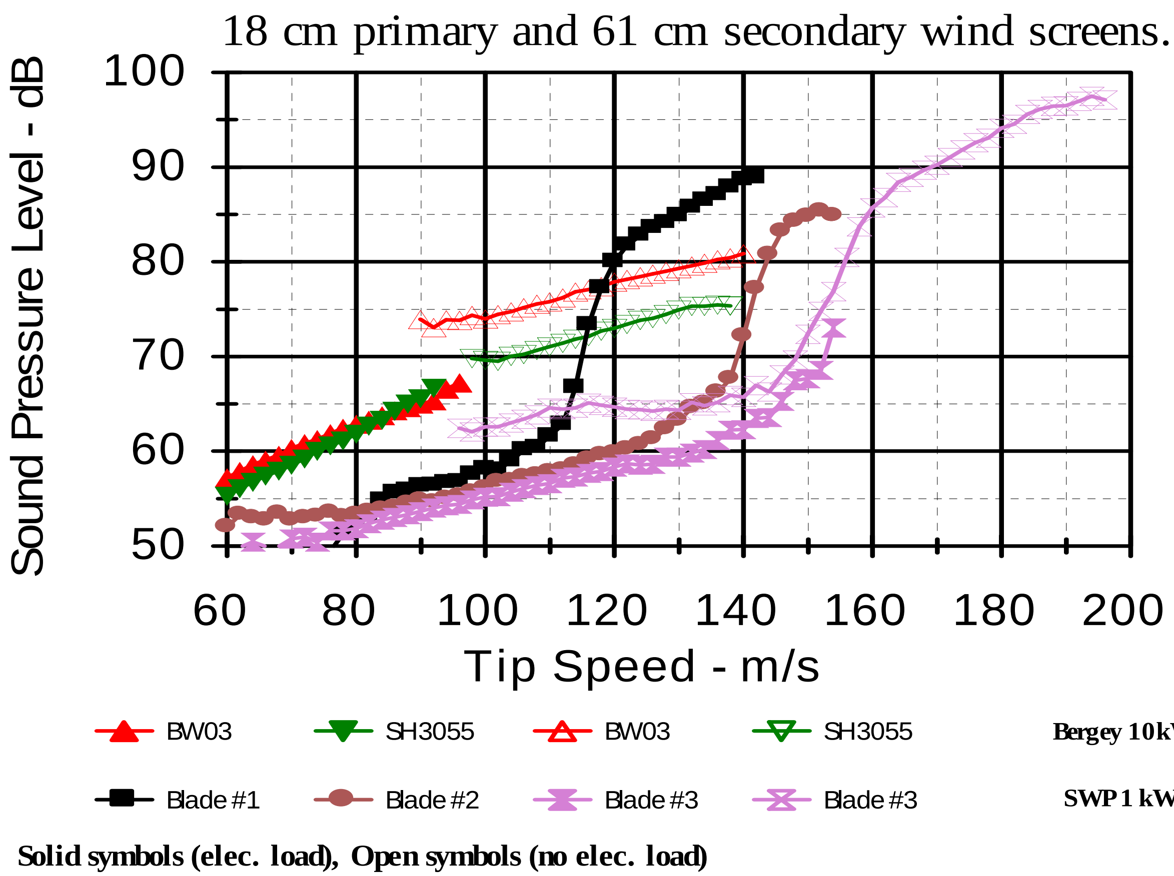

Fig. 20. SPL of Blades Tested on Bergey 10 kW and Southwest Wind Power 1 kW as a Function of Tip Speed.

CONCLUSIONS

For a particular wind turbine blade, a higher rotor speed will increase the sound pressure level (SPL). While operating in an unloaded or offline condition consistently leads to some increase in the SPL, the occurrence of flutter results in a dramatic increase. Generally, if the wind turbine can be kept online through use of a dump load or a lower furling wind speed, then the SPL should be acceptable to most people within close proximity of the wind turbine. Wind turbine blade fluttering was found to result in a SPL in excess of 80 dB, a level that most people find to be objectionable. An electrical dump load applied at a certain rotor rpm could prevent blade fluttering by slowing the wind turbine rotor down until the wind speed is high enough to furl the wind turbine rotor. When acoustical data is published, it is important to also show the rotor and/or tip speed, for the SPL is heavily dependent upon those speeds. In addition, for a non grid-tied system it is important to show the electrical loading of the wind turbine. Our main conclusion is that proper electrical loading of a small stand-alone wind turbine is more important for keeping noise levels down than further improvements in the design of the wind turbine blades.

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REFERENCES

1. 2005. Vick, B.D. and Clark, R.N. Performance and Acoustic Analysis of a Small Wind Turbine Used with a Helical Pump for Livestock Watering. Windpower 2005 Proceedings, May 15-18, Denver, CO, 11 pp.
2. 2004. Migliore, P. and Oerlemans, S. Wind Tunnel Aeroacoustic Tests of Six Airfoils for Use on Small Wind Turbines. NREL SR-500-34470, 2003.15 pp.
3. 2004. Selig, M. and McGranahan, B. Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines. NREL SR-500-34515, 19 pp.
4. 2003. Migliore, P., van Dam, J., and Huskey, A. Acoustic Tests of Small Wind Turbines, NREL/CP-500-34662. Oct., 2003. 14 pp. (Also presented at 2004 ASME Wind Energy Symposium, Reno, NV, Jan. 5-8, 2004)
5. 2002. International Electrotechnical Commission, Wind Turbine Generator Systems – Part 11: Acoustic noise Measurement Techniques. IEC 61400-11:2002(E), 43 pp.
6. 2000. Gipe, Paul, www.wind-works.org/articles/noiseswt.html
7. 1996. Wagner, S. Wind Turbine Noise. Springer. Berlin, New York, TJ828.W34, 204 p.