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Noise Propagation from a Vertical Axis Wind Turbine

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ABSTRACT

Initial noise measurements were performed on a 200kW vertical axis wind turbine (VAWT) and results were compared to that of a Vestas V27, a similar size horizontal axis wind turbine (HAWT). Multiple recording units were placed in line downwind of the turbine to investigate noise propagation. The frequency distribution of the noise were analyzed indicating that the VAWT has lower relative levels for frequencies under 3000 Hz, especially within 600-1200 Hz. Furthermore, VAWT noise seems to occur more around the same frequencies as the natural background noise, increasing masking probability. Results from propagation measurements seemed to indicate that noise declines more rapidly with distance for the VAWT then for the reference HAWT, possibly explained by the lower levels at low frequencies. Further investigation is needed to establish these differences and the 200 kW VAWT creates an opportunity doing so utilizing arguably the largest operational VAWT existing today.

Keywords: VAWT, Wind Turbine, Propagation I-INCE Classification of Subjects Number(s): 14.5.4

1. INTRODUCTION

Wind turbines can be categorized by the orientation of their axis of rotation into two groups: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). Even though the HAWT has by far been the most successful concept with the large and economically feasible turbines of today the VAWT concept has some advantages. VAWTs typically have fewer moving parts and a generator located at ground level which could ultimately lead to higher availability and lower maintenance cost (1). Furthermore, in (2) it has been shown that the concept is more suitable for up-scaling than the HAWT concept. And of special interest for this work, VAWTs has potentially lower noise emissions (1).

Noise is considered as one of the disadvantages with wind turbines and noise immissions at dwellings and other sensitive areas is generally regulated in national legislation which restrains potential locations when planning for wind power. For example, in Sweden, the sound intensity recommendations for noise created by wind turbines is set by the Swedish Environmental Protection Agency (SEPA) (3) to 40 dB(A) at dwellings which is further lowered to 35 dB(A) if obvious tones is present in the spectrum. 35 dB(A) is also the limit for specifically sensitive areas such as natural parks. These limits are based on the sound intensity created at a wind speed of 8 m/s, 10 m above ground and measured over 4 h. The definition of noise is simply unwanted sound (4). Distinguishing noise from sound is off course to a large extent subjective but generally sound from wind turbines is considered as unwanted and therefore it is referred to as noise in this work.

Extensive research has been presented regarding noise from wind turbines. For example, interesting work can be found in (5) where noise, sound masking and propagation modelling has been studied, in (6) where the human response to wind turbine noise has been investigated and in (7) where

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a substantial investigation of wind turbine noise in forestry areas is performed. However most research has been aimed at the more common HAWTs and little attention has been given to the alternative VAWTs which have shown potential for lower noise levels. VAWTs usually has lower tip speed ratio than HAWTs and should therefore produce less aerodynamic noise and furthermore the drive train of a VAWT can be placed at ground level which limits mechanical noise propagation (1). Work that has been done regarding noise from VAWTs include (8) and (9) where numerical methods are used to simulate aerodynamic noise from VAWTs and which for both studies indicates lower noise levels compared to HAWTs.

The VAWT we consider in this study is the so called H-rotor which is a Darrieus-type (10) turbine with straight blades. A 200 kW VAWT (hereafter referred to as the T1-turbine) was designed and erected by the company Vertical Wind AB in 2010. The turbine which is located just outside of Falkenberg at the west coast of Sweden is today owned by Uppsala University and the subject of research in a variety of fields. This particular VAWT has a direct drive permanent magnet synchronous generator which is mounted at the bottom of the tower and connected to the rotor by a steel shaft. Furthermore, it has a tower made out of laminated wood which from the start was free standing but after two years was complemented with support from three guy-wires.

Figure 1: The T1-turbine

In this study the frequency spectrum of the T1- turbine is studied and compared to that of a similar size HAWT to see how the frequency distribution differs. Noise propagation measurements are also performed for the two turbines to see if conclusions can be drawn regarding this aspect.

2. NOISE BEHAVIOUR

Sound is a pressure wave that travels through some kind of medium. Sound pressure is the difference between average local pressure and the pressure in the sound wave and the sound level is proportional to the square of that pressure compared to that of a reference level P_{ref} of 20 µPa (for air). The equivalent sound level is given in decibels (dB) by (4):

$$L_p = 20 \cdot \log_{10}\left(\frac{P}{P_{ref}}\right) \tag{1}$$

The most common way of measuring sound is by measuring all frequencies hearable by humans (20-20000 Hz) and presenting it as one single weighted reading. Since the human ear does not have the same perception for all frequencies a filter can be used to account for the relative loudness perceived by the human ear. The most common scale for environment noise assessment and the one generally used in laws and regulations is the A scale which gives the unit dB(A). (4)

Noise from operating wind turbines can be divided into aerodynamic and mechanical noise. Aerodynamic noise is of broadband character and occurs when the air flows around the blade and originates from various complex flow phenomena and generally increases with tip speed and hence the most sound is produced at or close to the tip of the blade. Mechanical noise originates from the relative motions of mechanical components in the gearbox, the generator, yaw drives, cooling fans, hydraulics and power electronics. For modern turbines the aerodynamic noise is generally dominant and in (11) it is shown that for a modern HAWT the most noise is created close to the wing tip when the blade travels downwards against the receiver and thus is amplified due to convective amplification. (4)

2.1 Distinguishing wind turbine sound

When recording noise from a wind turbine, the sound recorded L_{rec} consists of the wind turbine noise L_{wt} as well as the background sound L_{bg} which are related by (4):

$$L_{rec} = 10 \cdot \log_{10}(10^{L_{wt}/10} + 10^{L_{bg}/10}) \tag{2}$$

Recording with the wind turbine sequentially turned on and shut down, (2) can be used to separate the wind turbine sound level from the total sound level, if the wind and background sound conditions are unchanged.

2.2 Noise propagation of wind turbines

A simple model of a hemispherical sound propagation over a reflective surface and including air absorption is given by (4):

$$L_p = L_w - 20 \cdot \log_{10} r - \alpha r \tag{3}$$

Where L_p is the sound imission at the distance r from the source which has a sound emission L_w. The frequency dependent air absorption factor can for most conditions be set to α=0.005 dB(A)m^{-1}. Since both the air absorption and the absorption from the surrounding terrain increases with the frequency, noise of lower frequency travels further than that of higher. This in combination with that low frequency noise appears to be more disturbing (4) makes low levels at low frequencies an attractive attribute for wind turbines.

3. SETUP AND OBSERVATIONS

3.1 Experimental Setup

For recording the sound level of the wind turbine two channels were used at each measuring position, with one of the microphones having a wind protection muff which the other lacked. The two microphones were mounted on the same support, 1.5 m above ground and 0.6 m from each other. The microphones used were DBX-RTA-M measuring microphones normally used for reference measurements of wide bandwidth noise. These microphone is nearly omni-directional and has a very straight spectral response in the range of 20-20 000 Hz. The field recorder used were FOSTEX-2LE which samples with 24 bits sampling depth and at a speed of 44100 samples per seconds which is sufficient to measure signals at the higher end of the hearable sound spectrum. This entire setup was compiled for (7) where further information of the equipment can be found.

3.2 Data Processing

Data recorded from each of the instruments was read into Matlab as a wav-file from the compact flash card used in the digital recorder. Calibration data for each microphone was used to ensure correct mapping of the wav-data to sound pressure. Spectral information was then extracted using FFT on consecutive one second parts. Representative background sequences and wind-turbine-turned-on sequences were selected for each measurement (ensuring a near-constant background noise level). Sound pressure levels in dB(A) from the wind turbine are calculated from the difference in mean sound power of these sequences.

3.3 Calibration

One of the instruments was calibrated by the Swedish National test laboratory SP in Borås, Sweden. The rest of the instruments where then similarly calibrated against the one tested by SP. For further details of this procedure see (7). Furthermore, a second calibration was done on-site with all microphones placed in a row at the same distance

3.4 Observations

3.4.1 Thorsholm T1 200kW VAWT

The T1-turbine is situated in a plain field with a heavy trafficked freeway 750 m to its southwest. Furthermore there is a farm located nearby with its access road just 70 m from the turbine, this road is occasionally trafficked by heavy trucks which interfered some with the recordings. However, these interferences are appreciated to have small impact on the results due to the small part of the recording time they constitute and for the propagation results all microphones should have been interfered by approximately the same amount as the distance to the road is about equal, see figure 2. A number of recording units were set in line, downwind, starting 20 m from the turbine. Recordings of approximately 45 minutes were performed with the turbine first turned on and then off. Wind speed for both turbine and background recording was logged from the turbines own control system using a measurement mast situated 100 m from the turbine. In addition to these measurements, an earlier single microphone measurement at a mean wind speed 9.4 m/s (hub height) was used for comparing frequency distribution for different wind speeds. At this higher wind speed the turbine was operated at a tip speed below optimum and thus was stalling. The reason for this was a limitation of the rotational speed of 22 rpm called for by the added guy-wires that stiffens the tower so that the first mode eigen frequency of the tower is excited at 23 rpm. Since the rotational speed only was slightly lower than optimum, it is estimated that the effect of the stall was small and thus the appearance of the frequency spectrum not substantially influenced.

Table 1: T1 properties

Rated power	200 kW
Tower height	38 m
Rotational speed	16-33 rpm

Table 2: Measurements conditions

Length of wt segment	8 min
Length of bg segment	15 min
Wind speed hub height	6.4 m/s (mean)
Wind speed 10 m	5.2m/s (calc)
Rotational speed	16-21 rpm
Mic distances from wt	20, 40, 70, 100, 130, 160, 200
Recording date	2014-04-09

3.4.2 Kistinge Vestas V27 HAWT

A Vestas V27 with two fixed rotational speeds and pitch regulated blades were chosen to act as a reference when comparing the T1-turbine to a typical HAWT. This was chosen both because of its accessibility and its similarities regarding in size and the surrounding terrain compared to the T1 turbine. The V27 turbine is situated in a field with two identical turbines to its north, the closest one which could be accessed and thus was turned off during all measurements. The last turbine, which is situated 260 m away, was in operation during measurements. Furthermore there is a semi trafficked road approximately 160 m northeast of the turbine. On the opposite side of the road there is an industry and to the west there is a freeway 1100 m away at its closest but most of possible interfering noise is appreciated to come from the closer road or the neighboring turbine. A number of recording units were set in line, downwind, starting 20 m from the turbine. Recording of approximately 30 minutes were performed with the turbine first turned off and then turned on. The wind speed was estimated from viewing of the turbines own anemometer and seemed to be quite steady around 9 m/s during the entire recording.

Table 3: V27 Properties

Rated power	225 kW
Tower height	31.5 m
Rotational speed	33/43 rpm

Table 4: Measurements conditions

Length of wt segment	24 min
Length of bg segment	10 min
Wind speed hub height	9 m/s (approx.)
Wind speed 10 m	7.6 m/s (calc)
Rotational speed	43 rpm
Mic distances from wt	20, 40, 70, 90, 120, 150, 200
Recording date	2014-04-02

Figure 2: The T1 (left) andV27 turbine (right) with surroundings. Wind direction (red arrow) and microphone placement line (dashed). Upwards is north. [6]

4. RESULTS

4.1 Frequency of noise

In figure 3 and figure 5 the frequency spectrum respectively the frequency distribution for the T1 and V27 turbines can be seen, all recorded downwind at a distance of 40 m from the tower base. Looking at the spectrum, the V27 seem to have a broader spectrum with significant levels from 0 to around 2600 Hz whilst the T1-turbine seem to have lower levels at frequencies over 2000 Hz and slightly lower for frequencies below 500 Hz. In figure 5 it can also be seen that the T1-turbine has lower levels in the range of 600-1200 Hz. Comparing the frequency spectrums in figure 3, it seem like VAWT noise occur

[6] Source: kartor.eniro.se & maps.google.com

more around the same frequencies as the natural background noise, which increases masking probability (4). In figure 6 it can be seen that the behavior from the 6.4 m/s recordings is similar to that of the 9.4 m/s recording but the recording at higher wind speed shows even clearer that the T1-turbine has lower levels for all frequencies below 3000 Hz.

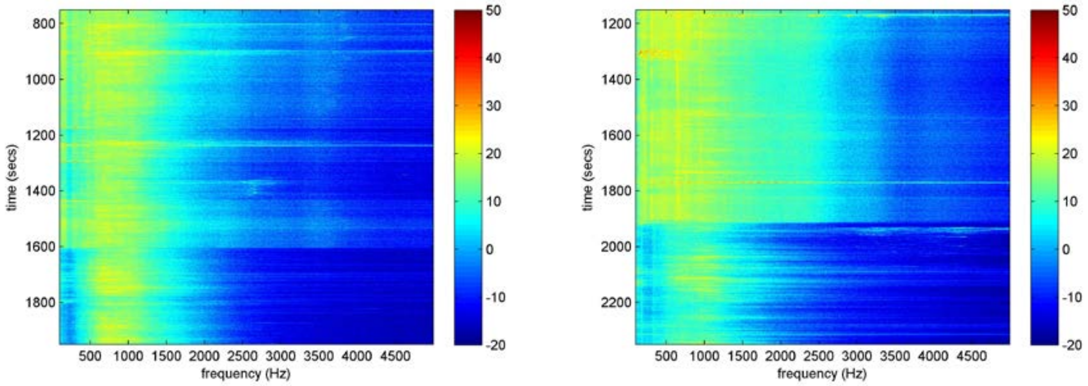

Figure 3: Frequency spectrum for T1 (left) and V27 (right). Turbines turned off at approx. 1600 respectively 1900 sec.

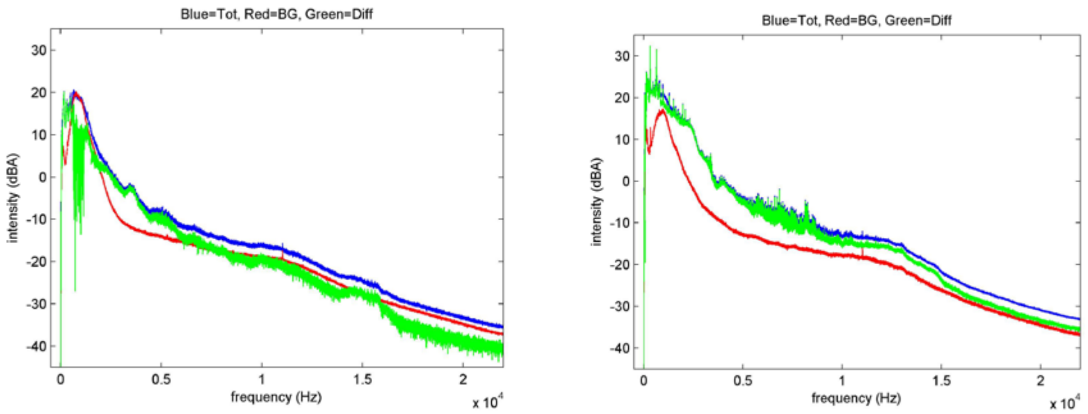

Figure 4: Frequency distribution for T1 (left) and V27 (right). Total noise in blue (highest for high frequencies), background noise in red (in middle for high frequencies) and difference between total and background noise in green (lowest for high frequencies).

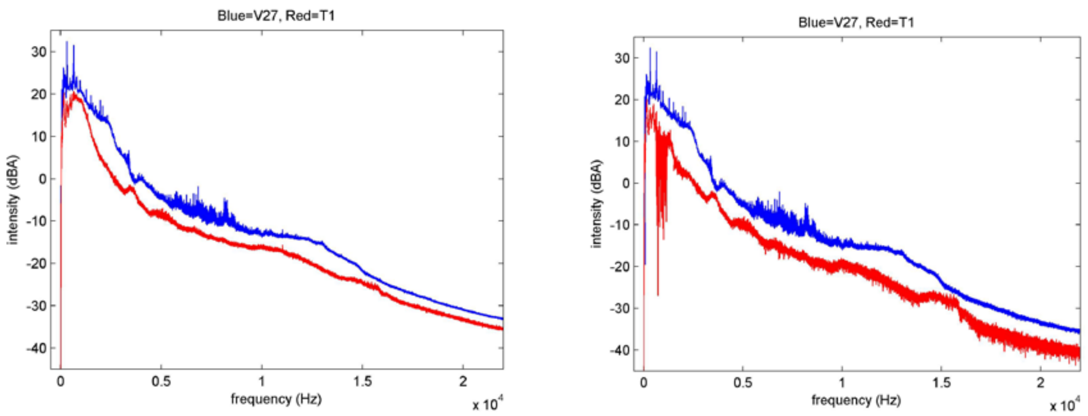

Figure 5: Comparison between T1 (red, lower) and V27 (blue, higher) regarding total noise (left) and turbine noise with background subtracted (right)

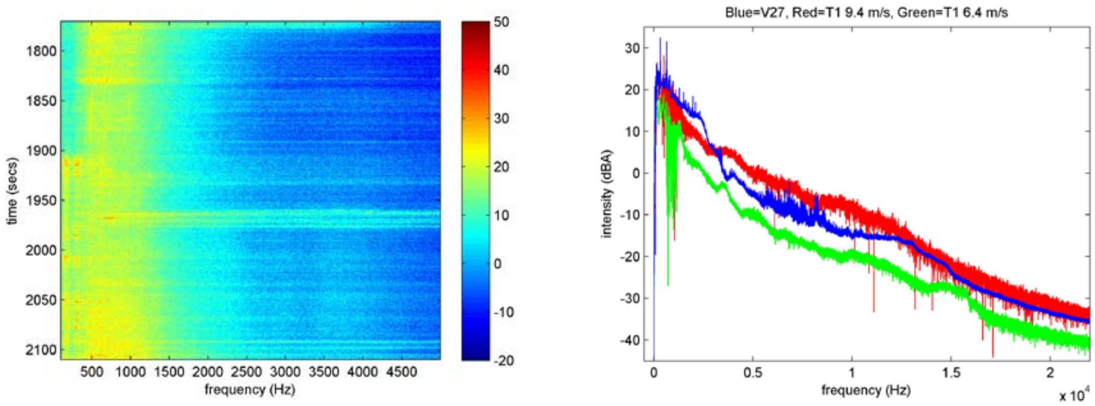

Figure 6: The frequency spectrum for the 9.4 m/s recording of the T1-tuirbine (turned on at approx. 1900 sec) and a comparison between the frequency distribution with background noise subtracted for the 6.4 m/s (green, lowest) and 9.4 m/s (red, highest for most frequencies) recordings for the T1-turbine as well as the V27 recording (blue, highest for low frequencies).

4.2 Noise propagation

The performed measurements indicates more rapid noise decline with distance for the T1-turbine compared to the V27. This can be seen in figure 7 where the noise levels as a function of distance are plotted for the T1 and V27 turbines respectively. The V27 curve is also projected on the T1 curve for easier comparison.

When creating the curves, appropriate segments representing background and wind turbine noise were chosen for both the V27 and T1 recordings. For the T1 recording the wind speed varied extensively so rather narrow segments had to be chosen to achieve the same mean wind speed for both background and turbine noise. This influences the reliability of the results which seem sensitive for how the segments are chosen, with this in mind, the more rapid noise decline of the T1-turbine still seem like a pattern. However, further measurements are needed to establish these findings.

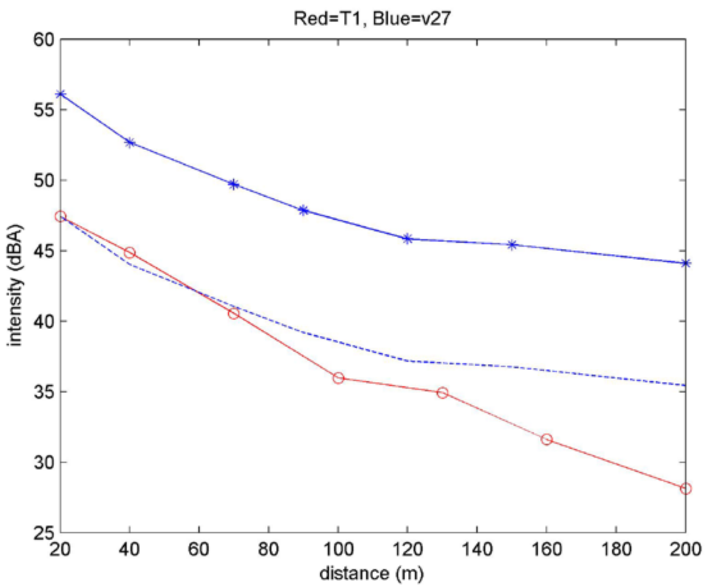

Figure 7: Noise propagation between T1 (red º) and V27 (blue *) turbines. Dashed blue line is the blue line projected for comparison

5. DISCUSSION AND CONCLUSIONS

Results show that the frequency spectrum differs between the T1-turbine and the similar size HAWT with lower levels for the VAWT turbine for frequencies under 3000 Hz, especially within 600-1200 Hz. Results from propagation measurements seem to indicate that noise declines more rapidly with distance for the T1-turbine then for the reference HAWT which could be explained by the lower levels at low frequencies. However, more recordings are needed to determine this difference in decline. Furthermore, VAWT noise seems to occur more around the same frequencies as the natural background noise, increasing masking probability. Previous work has shown that the VAWT concept has potentially lower noise emissions and if a potential for reduced low frequency levels and higher masking probability could be established the advantage towards HAWTs regarding noise could be further strengthened. The main conclusion of this paper is the necessity of further investigation of VAWT noise and the opportunity to establish potential advantages using the T1-turbine, possibly the largest operational VAWT existing today.

6. FUTURE WORK

More and longer measurements, especially during evenings with low and even background noise, are needed to verify or elaborate what is indicated in this paper regarding noise propagation. Deeper frequency analysis covering both the T1 turbine and modern large-scale HAWTs which are typically erected today should be done to better understand the fundamental differences regarding noise for the two concepts.

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