Experimental Measurement of Noise Production by a Small Scale Vertical Axis Wind Turbine

Kevin McLaren
0244415
ME 742 - Acoustics
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Background

One of the major public concerns with the widespread use of wind turbines for power production is excessive noise. For the most part, the large scale horizontal axis wind turbine (HAWT) is the most prevalent wind turbine design and as such has conjured the most attention in this regard. The majority of HAWT noise is generated from the gearbox used to transfer the low speed torque of the turbine into high speed torque suitable for electric generator operation, and the aerodynamic noise of the blades. The aerodynamic noise generated by HAWT's can mainly be attributed to vortices shed by the blades, impacting on the support structure as they pass by. As a result of previous experience with HAWT noise production it was expected that the increasingly popular vertical axis wind turbines (VAWT's), which have multiple blades passing in the wake of one another as well as the support structure, may have similar or increased noise production levels. Fortunately, due to the high RPM operation of VAWT's, a gearbox is not required and this source of noise can be avoided.

The goal of this project was to obtain quantitative data on the noise production of a small scale VAWT. Preliminary qualitative measurements of the turbine noise (listening to the turbine in operation) indicated that the noise production of the turbine was insignificant. However, nearby environmental factors such as vehicular traffic may have strongly affected these assessments. Evaluation of the turbine noise was accomplished by taking pressure measurements with a G.R.A.S. microphone at several different locations on the rooftop where the turbine is located both with and without the turbine in operation. Using the methods described within this course these measurements were analyzed to determine the sound pressure level (SPL), octave bands, overall SPL and A-weighted SPL of the turbine alone. This information was then used to conclusively determine whether the noise production of the VAWT under investigation is significant or not based on accepted noise standards.

Experimental Set-up

The turbine under investigation is a small scale VAWT consisting of three 3 m long vertically aligned blades each separated from one another by an angle of 120 degrees. Each blade is supported by two horizontal arms 1.25 m in length affixed to the central rotating shaft. The blade profile is a symmetric NACA0015 airfoil with a chord length of 0.4 m fixed at zero angle of attack to the support arms. The turbine is mounted atop a tower on the rooftop of the McMaster Innovation Park building in Hamilton, Canada. In order to acquire turbine noise level data for the given turbine under normal operating conditions, on-site pressure measurements needed to be obtained. As such, a portable measurement system was developed. This system consisted of a ¼" G.R.A.S microphone covered with a 3" diameter microphone cover mounted on a rigid mast at a height of 4.5 m (mid height of the turbine), a signal amplifier, a USB powered portable data acquisition card and a laptop for data processing and storage. This entire set-up was mounted on a utility cart to allow for measurements to be taken at different locations on the roof and can be seen in Figure 1 (power was supplied to the set-up via a 50 ft extension cord). In addition to the data acquisition system outlined above, a system to quantify local wind speed was employed. Due to the random nature of the wind, measurements of the wind speed over time needed to be obtained for future correlation of data. Fortunately, a propeller type anemometer designed to characterise the wind velocity profile over the surface of the rooftop was readily available. This anemometer was mounted on an additional mast at a height of 9 m and was located at a distance of 1 diameter (2.5 m) from the leading edge of the turbine (Figure 1).

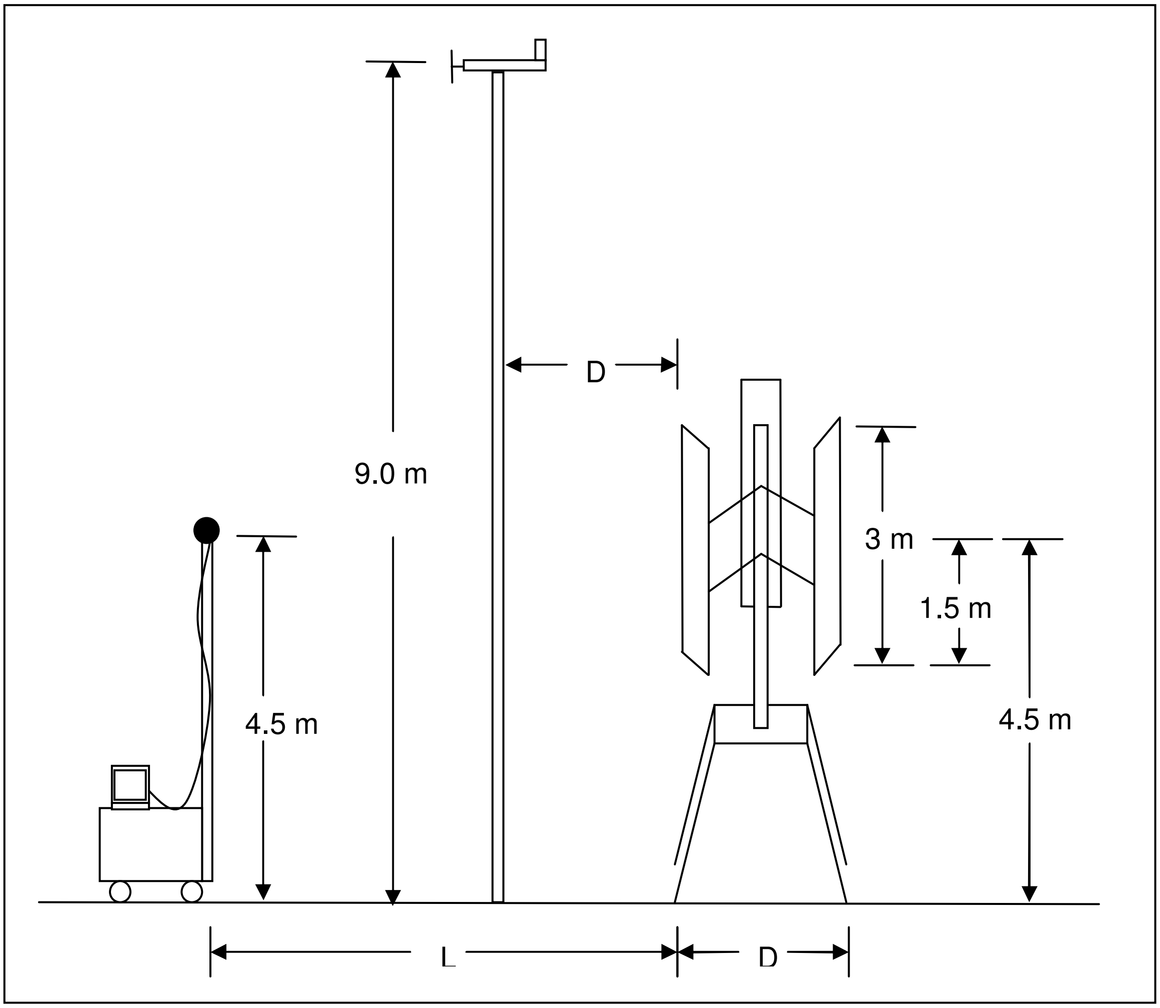


Figure 1: Experimental Set-up

Measurement Technique

In order to obtain a large cross-section of data to work with, a wide range of measurements were taken. Pressure measurements were recorded at 1 second intervals and averaged over a period of 1, 2, and 5 minutes in an effort to moderate the effects of the random nature of the wind velocity. These measurements were obtained at distances of L/D = 1, 2, 4, 7, and 10 in order to capture the effect of proximity to the wind turbine.

Measurements at each location were acquired with the turbine stationary in order to capture the background noise level as well as with the turbine in operation in order to capture the combined noise level of the turbine and background. Subtracting these two noise levels produces the noise level of the turbine in operation alone. In addition, multiple measurements were taken at each location at different times of the day in order to obtain data at a number of wind speeds. The ranges used to classify the wind speed will henceforth be classified as Low (< 11 m/s), Moderate (11 – 12 m/s) or High (> 13 m/s) where the available data permits. Unfortunately, data for small L/D at high wind speeds was not captured so these points were omitted from the results. Furthermore, inadequate data was obtained for low wind speed at L/D = 10 so this data is also omitted. Wind speed measurements were constantly recorded and logged at 1 second intervals through the use of a battery operated data logger mounted on the anemometer mast.

Data Processing

The initial signal obtained from the microphone was output as a voltage over time and a certain degree of data processing was required to convert this data into a useable form. First, taking the Fourier transform of this signal translates the data into the frequency domain at a sampling frequency of 1 Hz, but with uncalibrated signal amplitude. This signal was calibrated using a microphone calibrator which produces a 1000 Hz signal at a sound pressure level of 114.02 dB. Using the voltage output of this signal (0.014 V) as a reference and the following equation, a relationship between voltage output [mV] and pressure [Pa] was developed, where $20*10^{-6}$ Pa is the reference pressure.

$$\begin{aligned}1\,[Pa] &= (0.014084V * 1000mV/V)/(20*10^{-6}*10^{(114.02/20)}) \\ &= 1.4018\,[mV]\end{aligned}$$

Through the use of this calibration factor the scaled pressure and power spectrums were calculated. From the power spectrum the octave and 1/3 octave bands could then be calculated. This is a necessary step in processing the data in such a manner as to be able to calculate the overall sound pressure level of the turbine alone. The first step to producing the octave levels is to divide the frequency range into octave bands where the width of an octave band is determined through the use of a geometric series with a factor of 2. The central frequency f_c is defined as 2, 4, 8, 16, 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16000 Hz and the upper and lower band frequencies are defined as

$$f_n = f_c/\sqrt{2} \text{ = Lower Band Frequency}$$
$$f_{n+1} = f_c*\sqrt{2} \text{ = Upper Band Frequency}$$

The octave levels are then calculated by integrating the power spectrum over the width of an octave band and normalizing by a reference pressure to obtain the dB level of each octave [1].

$$Octave\ Level = 10*\log\left(\int_{f_n}^{f_{n+1}} \frac{P^2}{\left(20*10^{-6}\right)^2}\right)$$

The procedure for calculating the 1/3 octave bands is parallel to that of the octave bands outlined above with the exception that each octave band is further subdivided into 3 smaller bands. Figures 2, 3 and 4 below are a sample of the pressure spectrum, power spectrum, and a comparison of the pressure spectrum to the octave and 1/3 octave levels in dB respectively. This signal was acquired at a distance of 1D from the leading edge of the turbine while in operation at high wind speed.

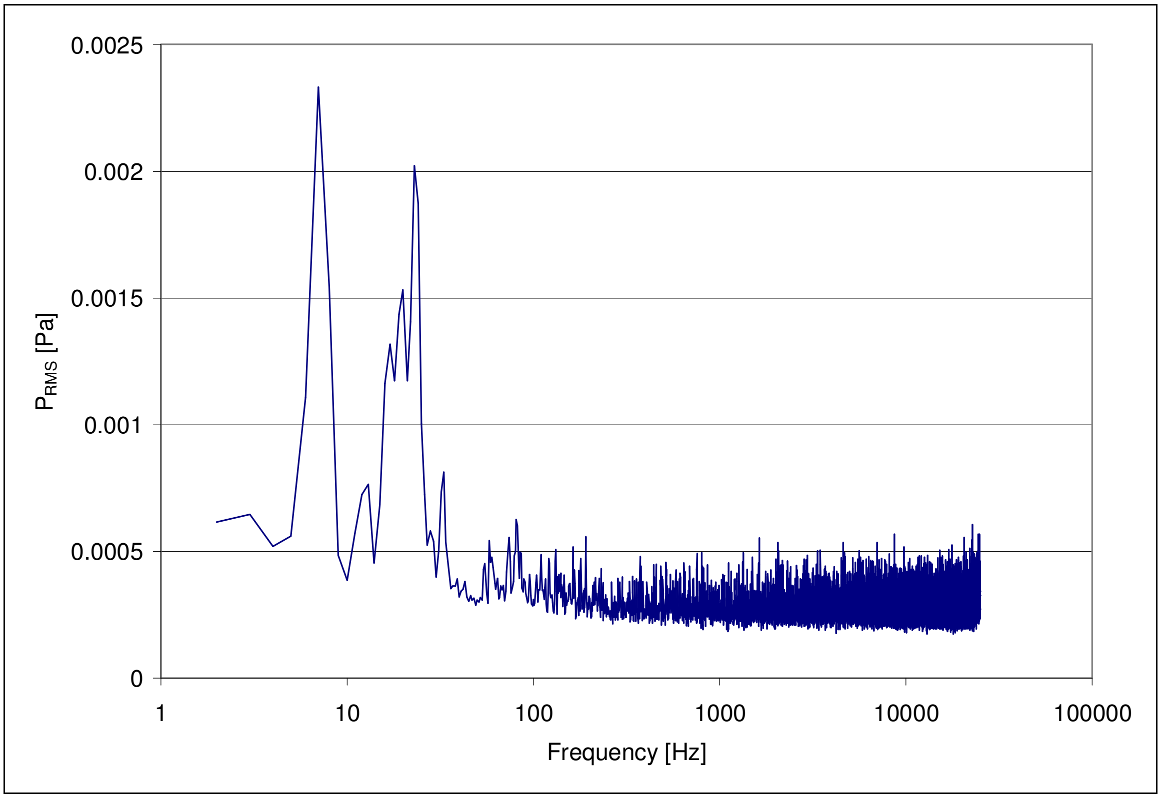


Figure 2: Sample Pressure Spectrum

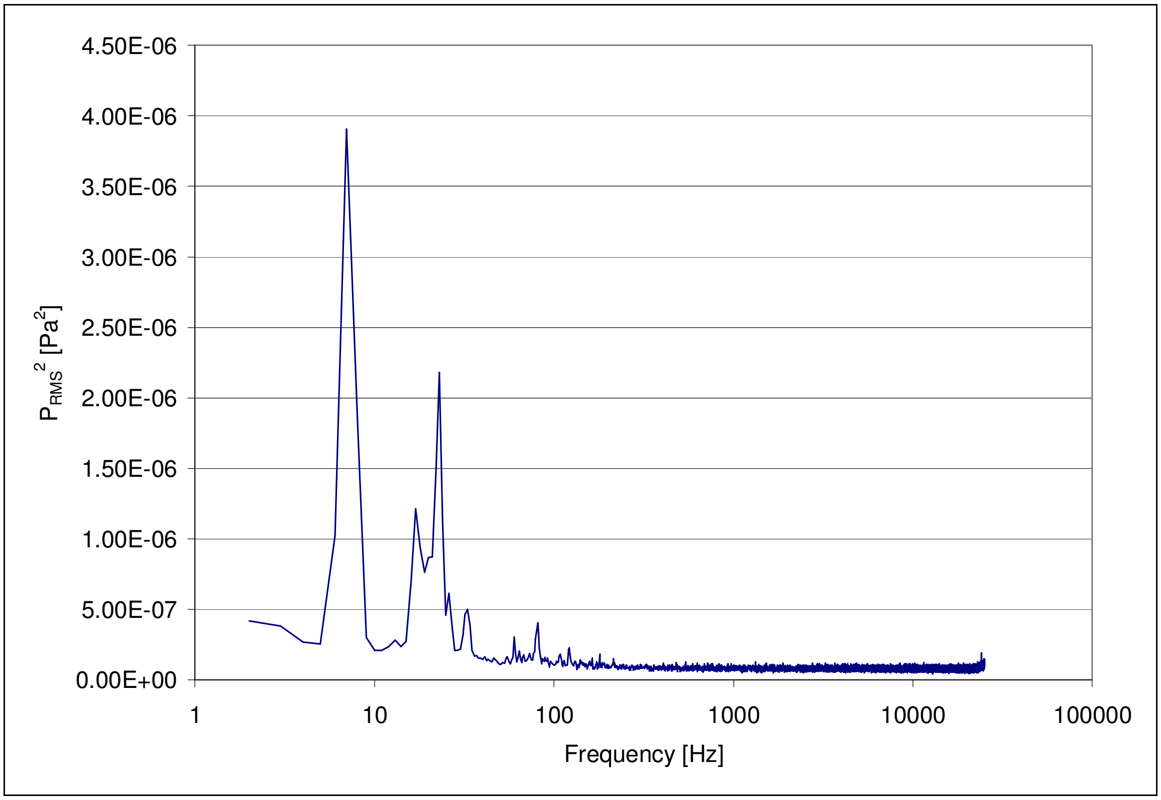


Figure 3: Sample Power Spectrum

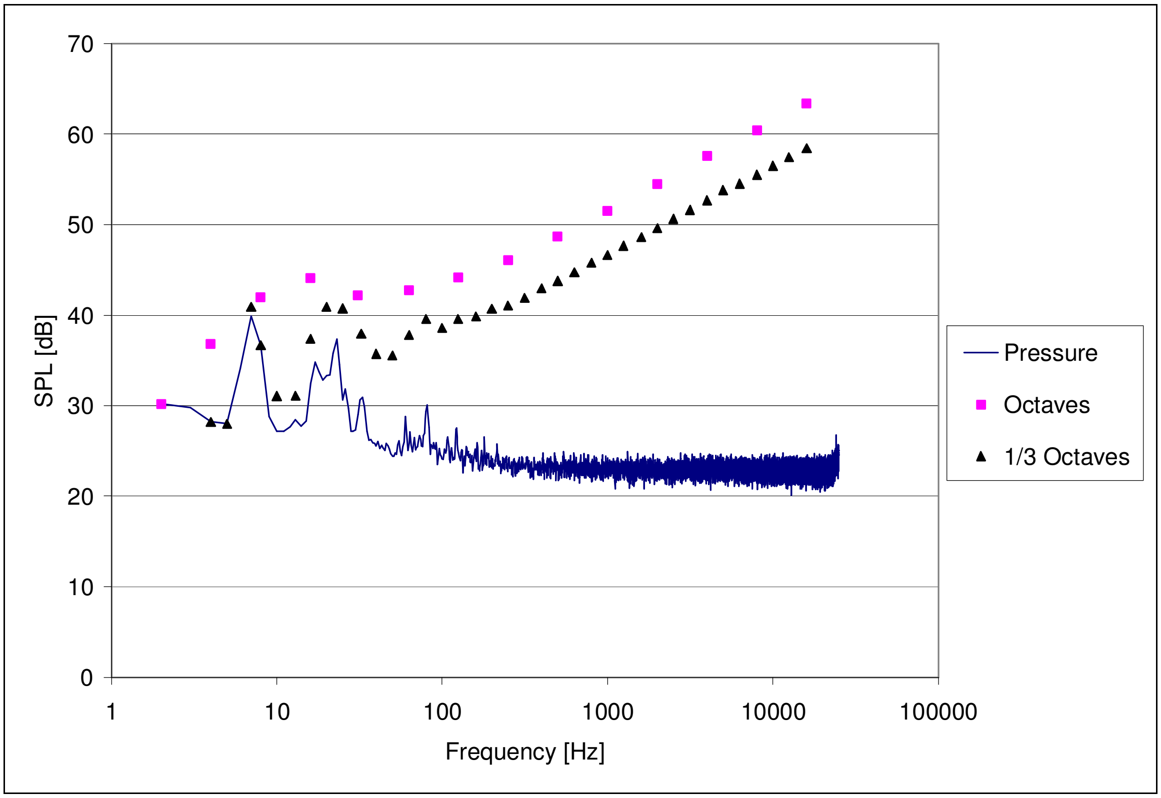


Figure 4: Sample Pressure Spectrum Including Octave and 1/3 Octave Levels

Results

From the previous section it is apparent that dominant peaks in the pressure signal at 7, 17, 23 and 33 Hz clearly exist within the pressure signal. For the given sample results the turbine was operating at a rotational velocity of approximately 140 RPM. This translates into a blade passing the upwind side of the turbine at $f \approx 7$ Hz and it can be speculated that this accounts for the large peak in pressure at this "blade pass" frequency. Additionally, the peak occurring at 23 Hz appears to be a higher harmonic of this frequency as it occurs at 3 times the dominant fundamental frequency. The less dominant peak at 17 Hz is not entirely understood and most likely is generated by background noise but interestingly enough has its first harmonic at a frequency of approx 33 Hz.

Further investigation into this behaviour is appropriate only after the background noise has been removed from the octave and 1/3 octave levels.

The linearly increasing slope in the octave levels beyond 100 Hz (Figure 4) can be attributed to what is known as “white noise”. In this high frequency range the pressure spectrum is relatively constant with respect to frequency. As a result, “since each successive octave of frequency will have twice as many Hz in its range, the power in white noise will increase by a factor of two for each octave band. Twice the power corresponds to a 3 dB increase, so white noise is said to increase 3 dB per octave in power. [2]” Similar behaviour can be observed in the 1/3 octave levels, where the dB level is increasing linearly at a rate of 1 dB per 1/3 octave band beyond a frequency of 100 Hz. Figure 4 also highlights the fact that the octave bands are to large to capture the finer details of the pressure spectrum while the 1/3 octave bands are able to properly represent this behaviour. As a result the 1/3 octave bands were used for all analysis henceforth.

To obtain an overall sound pressure level for the turbine at a given distance for a particular wind speed it is first necessary to subtract the 1/3 octave levels obtained without the turbine in operation from the 1/3 octave levels with the turbine in operation. This is accomplished as follows:

$$10 * \log\left(10^{T+back/10} - 10^{back/10}\right) = T$$

where *T* is the turbine noise and *back* is the background noise. Figure 5 is a sample of the 1/3 octave level subtraction at 4D from the turbine operating at high wind speed.

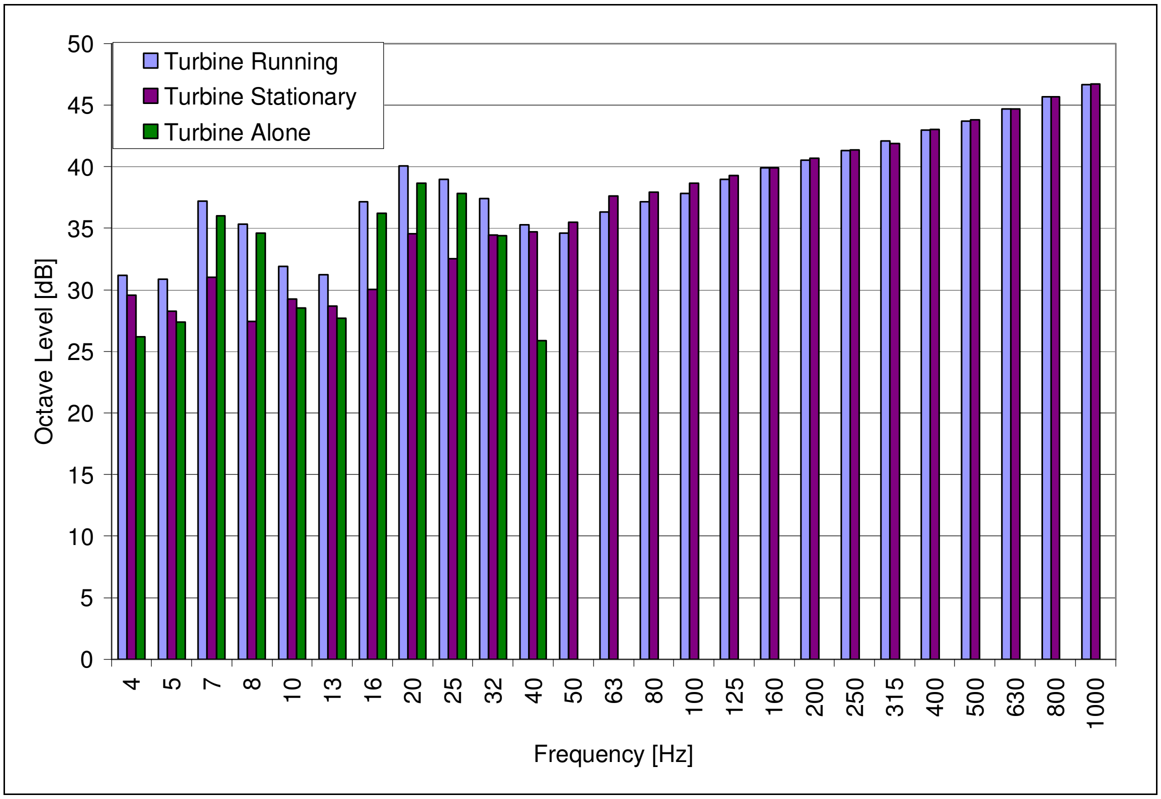


Figure 5: Sample Octave Level Subtraction

Observation of these results will reveal that under these conditions it is clear that the turbine does not produce any noise in the 1/3 octave bands beyond $f_c = 40$ Hz. Additionally, the majority of the turbine noise is generated at or near the blade passing frequency of 7 Hz and its higher harmonic at 20 Hz, while the pressure spikes at 17 and 33 Hz have been all but eliminated. The overall sound pressure level can now be determined by summing the octave levels of the turbine alone in a manner similar to the octave level subtraction previously performed. Figure 6 and 7 below show the dB and dBA level of the turbine alone as a function of wind speed and proximity to the turbine. Recall: due to available wind conditions and adequate data no measurements were obtained for high wind speeds at close proximity to the turbine or low wind speeds at large distances from the turbine.

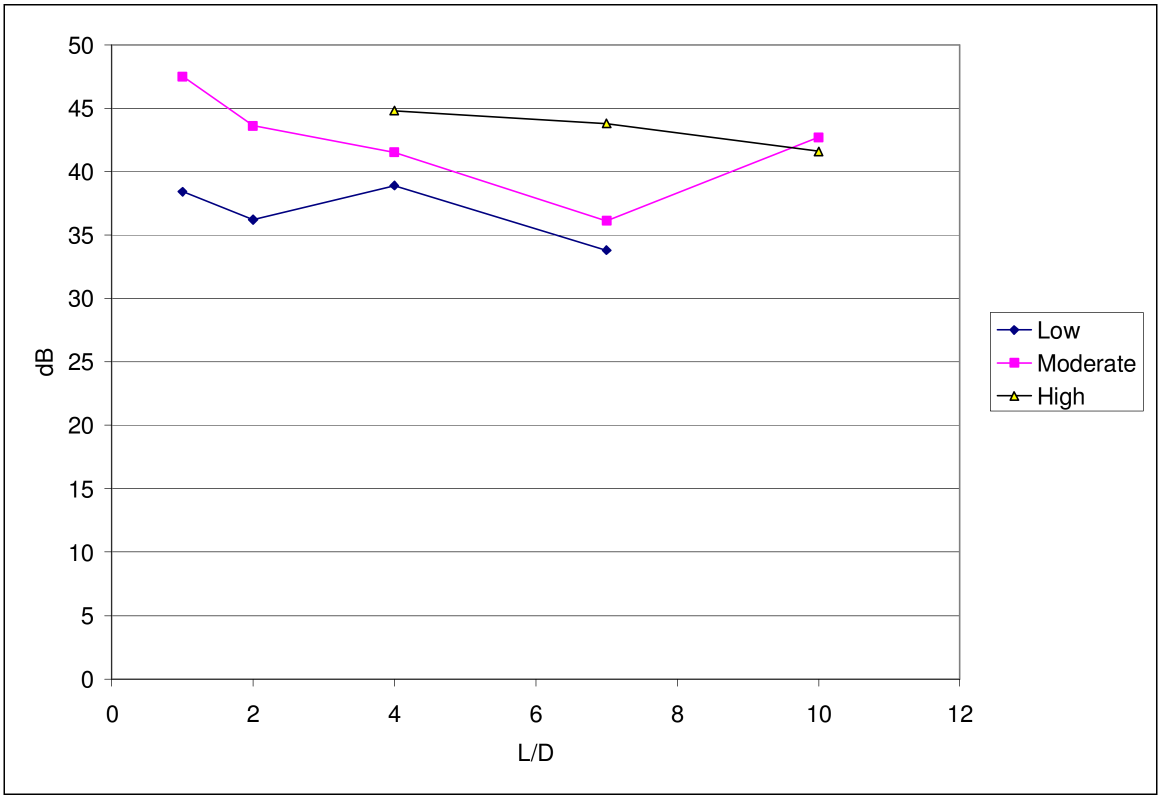


Figure 6: Turbine Noise in dB

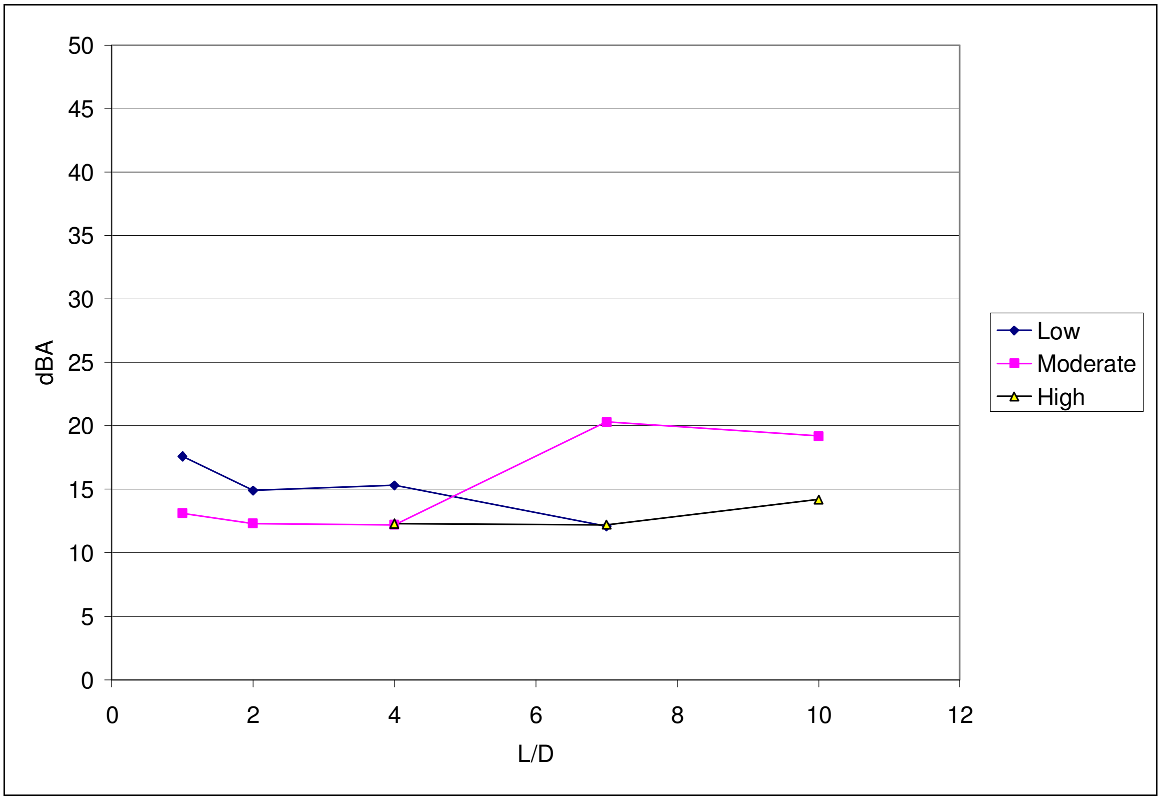
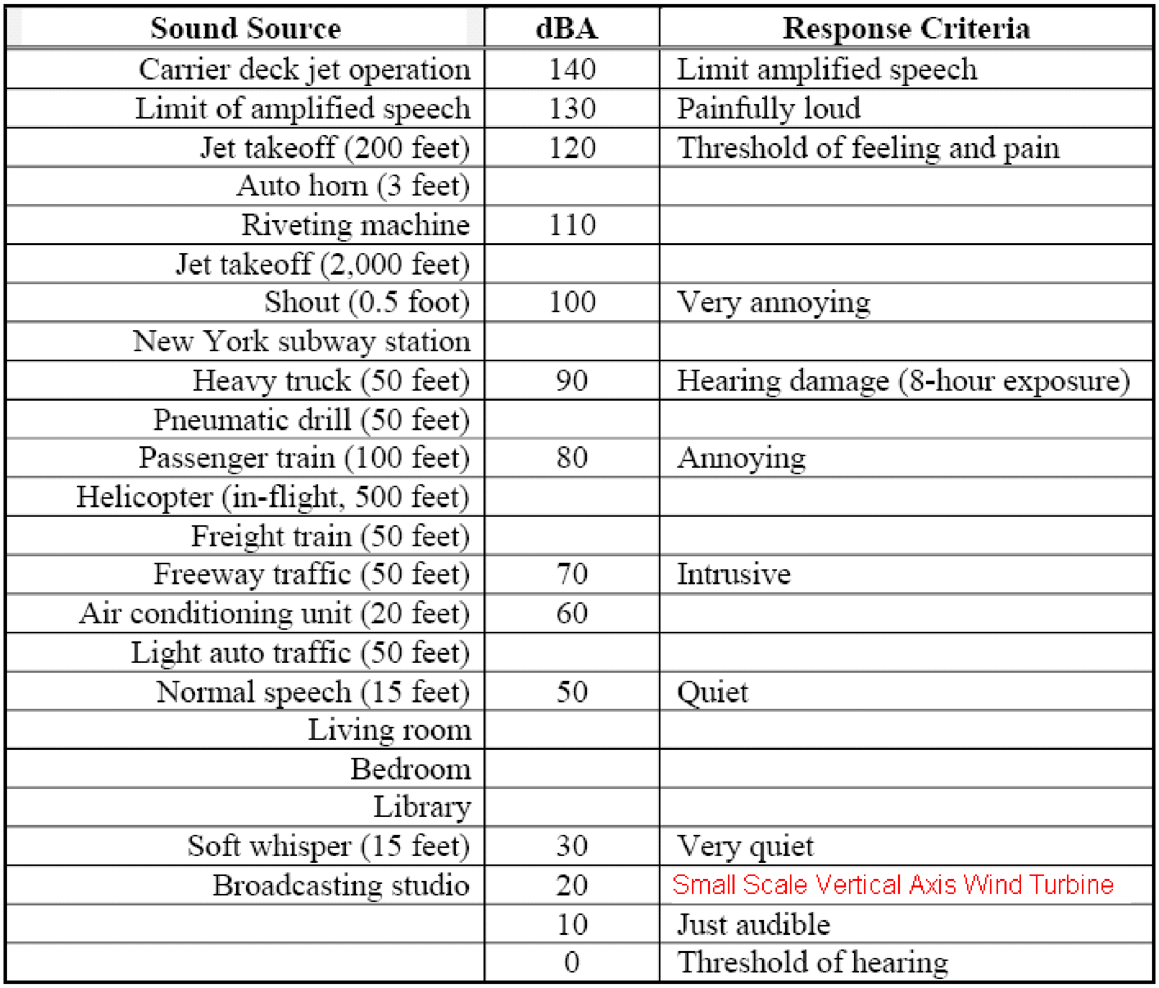


Figure 7: Turbine Noise in dBA

From Figure 6 it can be observed that the noise level of the turbine is both a function of the proximity to the wind turbine as well as the magnitude of the wind speed. As one moves toward the turbine the overall noise level increases by a small amount up until a distance of 1 Diameter which is the minimum safe distance that a person may approach the turbine while in operation. Furthermore, as the wind speed increases so does the noise level of the turbine. Again, this increase is minimal and the overall noise level of the turbine remains below 50 dB for all normal operating conditions (the turbine rarely operates at a wind speed beyond 15 m/s). In order to determine how the human ear perceives the turbine noise level the dB level is given an A-weighting based upon the average human hearing capability. Transferring the dB level of the turbine into the dBA scale (Figure 7) reveals that there is no strong correlation of the turbine noise with either proximity to the turbine or the wind speed level as was previously observed in the prior qualitative tests. Because the majority of the turbine noise is produced in the infrasound range (frequencies below human perception) the dBA level is greatly reduced from the dB level. This is because the A-weighting procedure minimizes the effect of very low and very high frequency noise on the overall sound pressure level.

Figure 8 [3] indicates at what noise level the turbine is in relation to other common noise sources. Clearly the turbine noise production even at just 1 Diameter is nearly imperceptible to the human ear. Furthermore, most regional standards place a maximum noise level production limit at approx. 50 dBA which is well above that of the given turbine.



Sound Source	dBA	Response Criteria
Carrier deck jet operation	140	Limit amplified speech
Limit of amplified speech	130	Painfully loud
Jet takeoff (200 feet)	120	Threshold of feeling and pain
Auto horn (3 feet)		
Riveting machine	110	
Jet takeoff (2,000 feet)		
Shout (0.5 foot)	100	Very annoying
New York subway station		
Heavy truck (50 feet)	90	Hearing damage (8-hour exposure)
Pneumatic drill (50 feet)		
Passenger train (100 feet)	80	Annoying
Helicopter (in-flight, 500 feet)		
Freight train (50 feet)		
Freeway traffic (50 feet)	70	Intrusive
Air conditioning unit (20 feet)	60	
Light auto traffic (50 feet)		
Normal speech (15 feet)	50	Quiet
Living room		
Bedroom		
Library		
Soft whisper (15 feet)	30	Very quiet
Broadcasting studio	20	Small Scale Vertical Axis Wind Turbine
	10	Just audible
	0	Threshold of hearing

Figure 8: Common Noise Production Levels

Conclusion

Based on the results of the preceding study it can be concluded that the noise level production of the small scale VAWT under investigation is insignificant and poses no threat to the comfort of nearby persons or wildlife.

References

[1] Kinsler, L.E., Frey, A.R., Coppens, A.B., and Sanders, J.V. Fundamentals of Acoustics. 4th Edition

[2] White noise (2006). Retrieved Dec 12, 2007, from Nave, C.R., Department of Physics and Astronomy, Georgia State University http://hyperphysics.phy-astr.gsu.edu/hbase/audio/equal.html

[3] Noise Level Assessment (2007). Retrieved Dec 13, 2007, from USDA Forest Service http://www.fs.fed.us/