45º CONGRESO ESPAÑOL DE ACÚSTICA
8º CONGRESO IBÉRICO DE ACÚSTICA
EUROPEAN SYMPOSIUM ON SMART CITIES AND ENVIRONMENTAL ACOUSTICS

CHARACTERIZATION OF THE ULTRASONIC ACOUSTIC FIELD OF A WIND TURBINE

PACS: 43.35.Yd

Ricardo Correia[1], José Vieira[1], Carlos Faneca[1], Daniel Albuquerque[1], Carlos Bastos[1], Hugo Costa[2], Joana Bernardino[2], Miguel Mascarenhas[3], Maria João Pereira[4], Carlos Fonseca[4], Octávio Inácio[5]

[1]Department of Electronics Telecomunications and Informatics, University of Aveiro
{rjoao, carlos.faneca, dfa, jnvieira, cbastos}@ua.pt

[2]Bio3 - Estudos e Projectos em Biologia e Valorização de Recursos Naturais, Lda. Almada, Portugal
{hugo.costa, joana.bernardino}@bio3.pt

[3]Sarimay - Ambiente, Energia e Projectos, S.A. Lisboa, Portugal
mtm@sarimay.com

[4]Centre for Environmental and Marine Studies, University of Aveiro
{mariajoaopereira, c.fonseca}@ua.pt

[5]Escola Superior de Música, Artes e Espectáculo – Instituto Politécnico de Lisboa
octavioInacio@esmae.ipp.pt

Abstract

Wind energy is a sector of the alternative energy industry that is growing worldwide. However, there are concerns regarding bat fatalities at wind turbines. This phenomenon is widespread and has received attention to warrant investigation into how and why these collisions occur. In this paper we characterize the ultrasonic acoustic field of a wind turbine in order to find out if the turbines emit ultrasound. We conducted this study at Serra dos Candeeiros near Lisbon, Portugal, where some bats have been found injured or dead beneath wind turbines [1]. The measurements were divided into 3 different campaigns: 1) seven acquisitions at ground level in front of the nacelle, 2) five acquisitions around the turbine at ground level and 3) one acquisition inside the nacelle. The analysis of the results shows that the analysed wind turbine does not reveal any ultrasound noise source.

1 INTRODUCTION

There is a concern for the possible adverse environmental impact of noise from large horizontal axis wind turbines operated for electric power generation. The incidence of bat-turbine interaction provides an interesting problem from an acoustic and also engineering point of view, and it is clear that an immediate solution is needed not only to minimize the impact on existing bat populations (particularly for endangered species), but also to free the way for a complete development of the wind energy. Several studies [2]–[5] indicate that migratory tree-roosting bats are being killed in unprecedented numbers at wind power facilities. Bats may be killed directly by moving blades, by simply colliding with stationary turbine structures such as the monopole (the structure on which the turbine generator and blades are mounted). A large percentage of observed bat fatality may be due to barotrauma, i.e., injury resulting from suddenly altered air pressure. Fast-moving wind turbines blades create vortices and turbulence in their wakes, and it has been hypothesized that bats experience rapid pressure changes as they pass through this disturbed air, potentially causing internal injuries leading to death. There are some hypotheses that may account for the discovery of injured, dead, or moribund bats on the ground beneath and near turbines. Flying bats may randomly come into contact with rotating blades. Because the high frequencies attenuate quickly in air [6] (see Figure 1), the range of the bats sonar is limited to few meters and bats may not have time to move out of the path of the blades by the time they are able to detect its presence. Another hypothesis is that bats may be attracted to wind turbines due to the audible sounds and ultrasounds produced by rotating blades, generator operation, or other moving components of the turbine. Some authors believe that several factors may be causing an increased density of bats in the general area of wind energy facilities [7]. In [8] the authors show that due to the limitation on the bats hearing system they could not hear the Doppler shift caused on the ultrasounds by the moving blades. Moreover, the bats would need more than 50 calls to detect the moving blades. Due to this, they concluded that the bats could not detect the blades and can be easily harmed.

The Figure 1 shows the attenuation of the sound for different distances and frequencies in the air for a temperature of 22 ◦C and an air humidity of 80 %. Picking two examples for a frequency of 80 kHz, we have for a distance of 10 meters an attenuation around 40 dB and for a distance of 40 meters we have an attenuation of 120 dB. From these two examples we can see that even if the wind turbines produce noise signals with ultrasonic components, its effect will vanish after a few tens of meters of propagation. Even though, we decided to measure the sound field around a wind turbine in order to verify if there is any frequency components in the audible and non-audible frequency range that can explain why some species of bats are potentially attracted to the wind turbines [9].

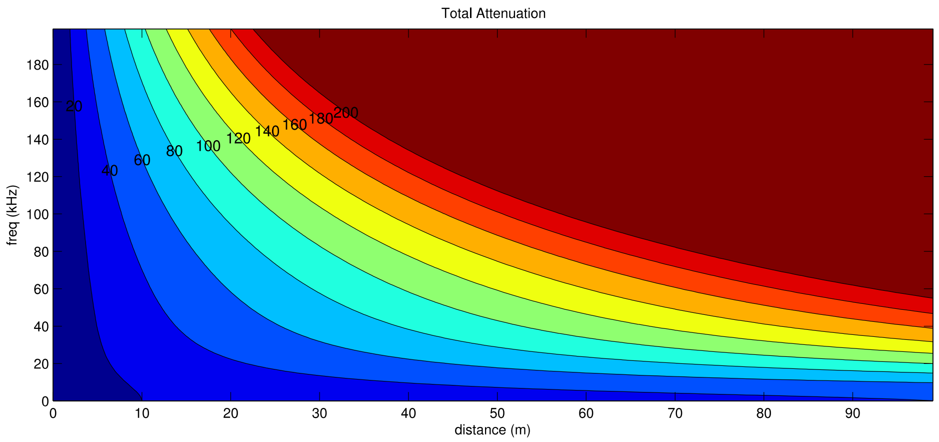


Figure 1. Attenuation in dB of the sound in the air as a function of the propagation distance and frequency while considering an air temperature of 22 °C and an air humidity of 80 %.

2 STUDY AREA

To characterize the sound and ultra-sound field of wind turbines, we conduct two trips to the Serra dos Candeeiros wind farm, since the experimental setup used in the first measurements introduced some electrical noise in the measurements. It was therefore necessary to repeat some of the measurements around the turbine, with more compact equipment, which made the measurements easier to take and also more immune to electrical interferences. This second set of measurements was also implemented inside the nacelle. The wind farm where measurements were taken is located in Serra dos Candeeiros (Portugal), with wind turbines from Vestas model V90.

Figure 2 shows a map of the Serra dos Candeeiros supplied by the promoter. The wind turbine where the tests were realized is indicated with a red circle and had the identification number 23. The GPS coordinates of the turbine are 39°25’58.73"N, 8°55’20.49"W.

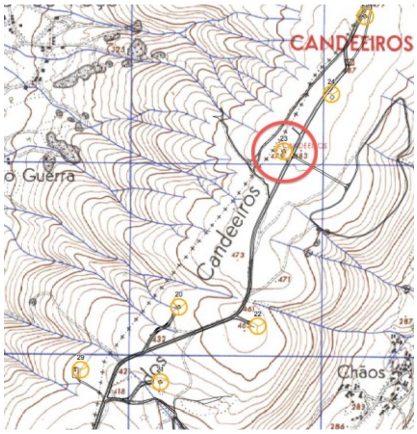


Figure 2. Map of Serra dos Candeeiros where the red circle indicates the position of wind turbine number 23.

The wind turbine has a hub height of 80 m, a blade length of 44 m and a rated power of 3000 kW. It has a rated wind speed of 15 m/s and a cut-in wind speed of 3.5 m/s. The rotor has an operational interval in the range 6.6 rpm – 18.4 rpm.

3 THE MEASUREMENT SETUP

In this work we want to characterize the noise emitted by a wind turbine including the ultrasound range of frequencies, that is the frequency range above 20 kHz, which is considered the highest frequency that an human been can hear [10]. However, the companies that produce calibrated equipment to measure sound pressure level do not cover the ultrasonic range of frequencies. This is a common problem to other similar studies, see for example [9], where uncalibrated sound recording equipment was used. Due to this problem we decided to use calibrated microphones and high quality audio sound cards with a frequency range enough to acquire ultrasounds. In order to have noise measurements in sound pressure level and Pascal units we had to calibrate the whole measurement setup manually. On the remain of this section, we briefly describe the characterization of the measurement setups and their calibration.

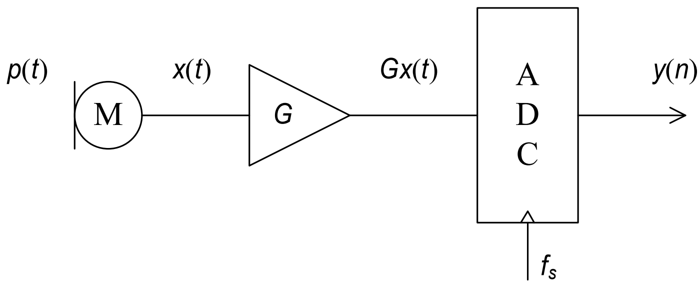


Figure 3. Generic model of the measurement chain with the microphone the pre-amplifier with gain *G* and the ADC.

The measurement chain is composed by a microphone M with sensitivity S[mV/PA], an amplifier with gain *G* and a Analog to Digital Converter (ADC) as shown in Figure 3. For our measurements we have used two different microphones, the 1/4" Brüel microphone model 4954A and the Sanken model CO-100K, which were calibrated by the manufacturers that provide individually sensitivity measurements. The Brüel microphone has a wide bandwidth and allows us to perform our measurements with complete confidence on the sensitivity curve given by the manufacturer. However, this microphone needs an external power supply. The Sanken microphone does not need any external power supply and can be directly connected to a professional sound card with phantom power making the measurement setup more convenient.

As we decided to show the results in Sound Pressure Level using Pascal units we need to characterize the setup measurement of Figure 3. Consider the acoustic signal $p(t)$ and its RMS (Root Mean Square) value given by

$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T p^2(t)\,dt} \qquad [\mathrm{Pa}] \tag{1}$$

The sensitivity S in [mV/Pa] of a microphone indicates the effective value of the microphone output voltage, x_{rms} when subjected to an acoustic signal with an effective value of p_{rms} [Pa]. So we can write

$$x_{rms} = \frac{S}{1000} p_{rms} \qquad [\mathrm{V}] \tag{2}$$

At the input of the ADC we have the signal $Gx(t)$. If the input voltage of the ADC varies between $\pm V_{max}$ values corresponding to $y(n) = \pm 1$, we have

$$y_{rms} = \frac{G}{V_{\max}} x_{rms} \qquad [\mathrm{V}] \tag{3}$$

and using (2) we finally have

$$p_{rms} = \frac{1000 V_{\max}}{SG} y_{rms} \qquad [\mathrm{Pa}] \tag{4}$$

The sound pressure level is defined in dB by

$$Lp = 20\log_{10}\frac{p_{rms}}{p_0} \qquad [\mathrm{dB}] \tag{5}$$

with p_0 = 20µN/m^2 [µPa]. Finally we obtain the Lp in function of y_{rms}

$$Lp = 20\log_{10}\frac{V_{\max} 5 \cdot 10^7}{SG} y_{rms} \qquad [\mathrm{dB}] \tag{6}$$

For the measurements we have used three different setups. We will present them as well as the measures of the gains G and V_{max}.

3.1 Setup 1

This setup is described in Figure 4 and consists of a microphone Brüel 1/4″, type 4954A powered by a Detatron power supply Brüel WB 1372 and the recorder TASCAM DR-680. The use of the recorder powered by batteries, allowed faster measurements and avoided electrical interference. The gain of the recorder can be set by the "TRIM" ranging between −31 dB and +31 dB, and the switch "LOW +3 dB / HIGH +27 dB ".

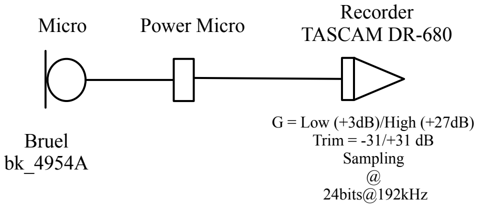


Figure 4. Setup 1 for signal acquisition based on recorder TASCAM DR-680.

3.2 Setup 2

This setup is presented in Figure 5 and consists of a microphone Sanken CO-100K and the recorder TASCAM DR-680. For this setup and the previous one we used a sampling rate of 192 kHz and 24 bits per sample. The acquisitions were recorded to a SD memory card and transferred to a computer.

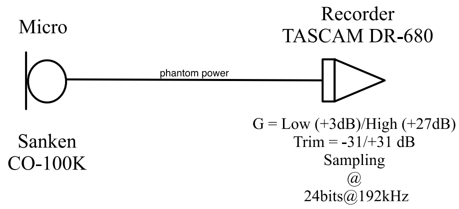


Figure 5. Setup 2 for the signal acquisition using the same recorder from TASCAM but a Sanken microphone with phantom power.

3.3 Setup 3

This last setup can be observed in Figure 6, and it comprises a microphone Brüel 1/4″ type 4954-A), powered by a Detatron power supply Brüel WB 1372, an amplifier developed at the University Aveiro, a sound card Edirol Audio Capture FA-66 with firewire interface and a laptop Macbook 13". For recording the signals we used the program Audacity. For each measurement we recorded 1 minute of sound, using a sampling frequency of 192 kHz and 24 bits per sample.

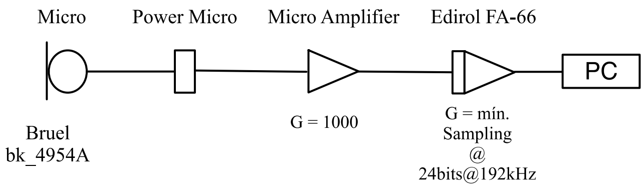


Figure 6. Setup 3 for signal acquisition using an Edirol FA-66 sound card and a portable computer.

4 THE MEASUREMENTS

The measurements at the wind farm were divided into three different acquisition campaigns. We present here each one of the acquisition campaigns.

4.1 Acquisition Campaign 1

This first acquisition consisted on the measurements schematized in Figure 7, using Setup 1 of Figure 4, with acquisitions at ground level in front of the nacelle. The measurements were taken with the microphone positioned at the following distances 128, 64, 32, 16, 8, 4 and 2 m. The wind speed measured during these measurements was between 2 and 3 m/s at ground level. For each one of the seven distances 1 minute of signal was acquired using a total gain G = 33 dB ("High" and TRIM = 6 dB).

4.1.1 Campaign 1 results

In Figure 8 we can see the SPL spectrum of this acquisition. As we can observe, above the 20 kHz we did not found any source of ultrasounds coming from the wind turbine, even for the shortest distance of 2 m. However, for low frequencies we can see that the noise coming from the wind turbines was much higher. In the Figure 8 we can see that it goes up to 73 dB. In this power spectrum we can also see a small peak at the frequency of 100 Hz originated by the mains power interference.

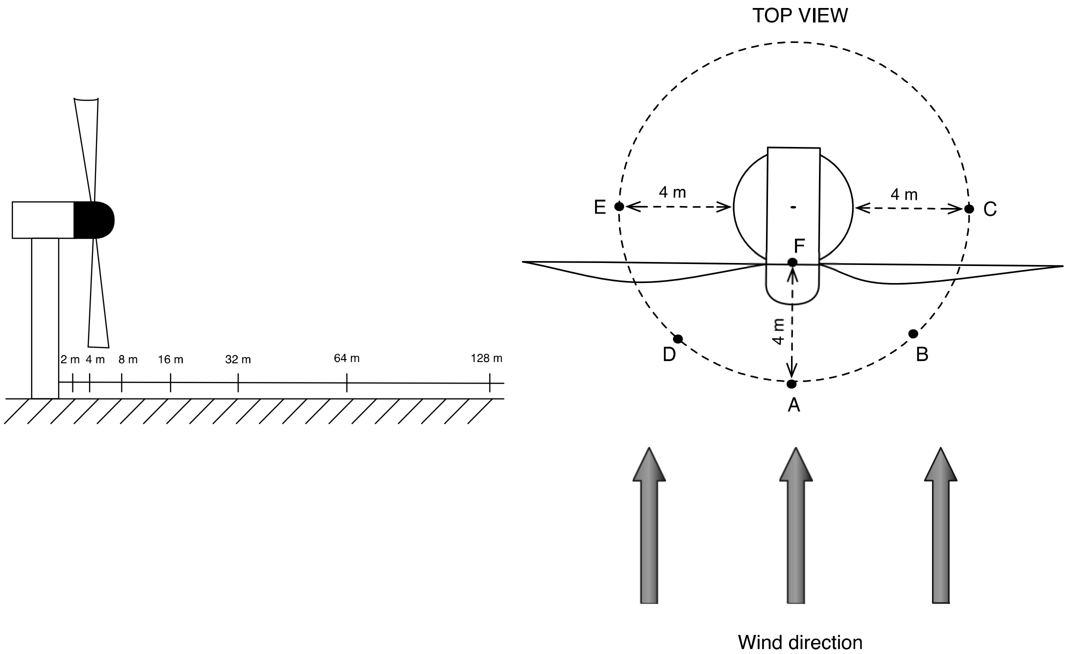


Figure 7. Different measurement setups used. In the left we took 7 measurements at ground level from 2 m to 128 m for the acquisition campaign 1. At the right we present the several acquisitions took around the wind turbine for the acquisition campaign 2.

4.2 Acquisition Campaign 2

The second acquisition campaign, shown in Figure 7, consisted of five measurements, around the turbine at ground level, at a distance of 4 m from the wind turbine tower, using Setup 1.

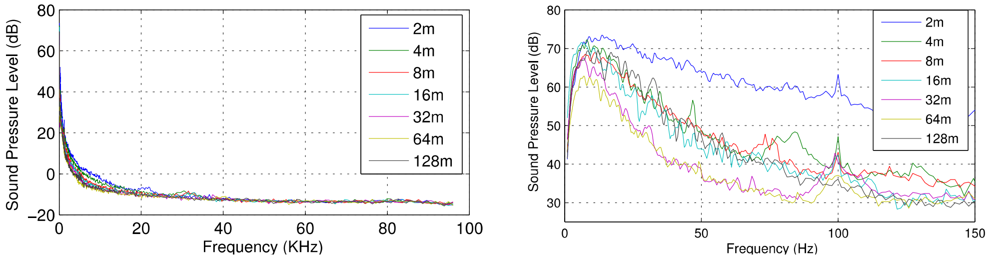
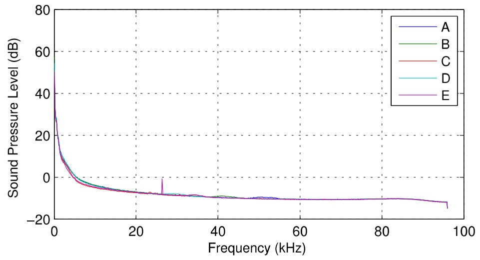


Figure 8. Measurements at ground level in front of nacelle for the various distances (left). In the right power spectrum we can see that for the low frequencies – from 20 Hz to 150 Hz – the SPL can attain more than 70 dB.

These acquisitions were obtained at five points A, B, C, D and E, each with a duration of 1 minute with a total gain of 33 dB ("High" and TRIM = 6 dB). In this campaign, two more acquisitions were made, one at the point A and the other at point F, each with a duration of 1 minute and a total gain of 47 dB ("High" and TRIM = 20 dB).

4.2.1 Campaign 2 results

As we can see in the Figure 9 the power spectrum of the acquisitions taken around the turbine do not show any source of ultrasound acoustic signals. The small peak that we can observe at a frequency near 30 kHz was originated by the electronic system of the wind turbine. We have acquired signal without microphone at the same position and we get the same interference.



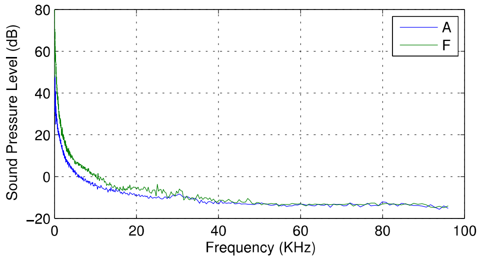


Figure 9. Power spectrum of the signals captured around the turbine during campaign 2. In the right spectrum we have measurements for points A and F with higher gain.

4.3 Acquisition Campaign 3

The third acquisition campaign consisted in a measurement with a duration of 15 minutes, inside the nacelle. The acquisition was cropped to 1 minute and a total gain of 3 dB ("Low" and TRIM = 0) was used. We used Setup 2 (Figure 5) for this measurement with the microphone Sanken CO-100K and the acquisition was obtained between the generator and the gearbox.

4.3.1 Campaign 3 results

We decide to measure the noise inside the nacelle in order to verify the amount of noise produced by the gearbox, the generator and other equipment. In the Figure 10 we can see the power spectrum of the noise inside the nacelle. The amount of noise in the ultrasound band is much higher than the one present in the measurements performed outside. We were not able to find any evidence of the kind of isolation the nacelle of the Vestas V90 wind turbine has. The company does not have any online information about the isolation properties of the nacelle. However, from our measurements we can say that most of the noise captured outside is aerodynamic noise, which can mean that the nacelle has some effective noise isolation.

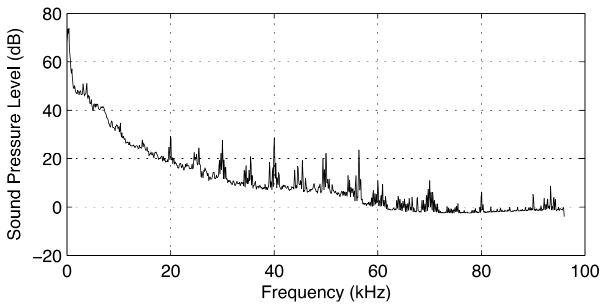


Figure 10. Power spectrum of the noise measured inside the wind turbine nacelle.

5 DISCUSSION

The main goal of this work was to answer the question: Are the bats attracted by ultrasounds produced by the wind turbines? We only answer this question partially. Firstly we did not measured the sound emitted by the wind turbine for all the possible directions. Secondly, we only measured the noise emitted by one wind turbine model the V90 from Vestas. Other wind turbines can have different noise isolation in the nacelle or produce different noise. As we have mentioned, the measurement campaigns 1 and 2 performed at the ground level did not reveal any ultrasound noise source. The measurements performed inside the nacelle showed, as expected, some noise in the ultrasound region. However, this noise seems to be quite well isolated and none is detected outside the nacelle.

Considering the measurements performed, we can say that the V90, Vestas wind turbine is not a source of any ultrasound signal that eventually could attract bats to it. This result is inline with other similar studies performed with different wind turbines [9]. As mentioned in the report [11] one possible idea to explain the attraction of the bats to wind turbines, is the Doppler effect caused by the rotating blades on their aerodynamic noise. As the hearing system of the bats is quite sensitive to the Doppler effect, maybe this hypothesis can deserve further attention. Using one of the acquisitions performed at ground level at a distance of 128 m, we can see in the Figure 11 a spectrogram of the noise produced by the wind turbine. As we can see, the frequency components changing in time according to the movement of the rotating blades.

Although a p_0 reference sound pressure of 20µP has been used, further research should be carried on what this reference value should be for bats. This way the sound pressure level would reflect the hearing ability of the animal and a comparison with other researchers results could be more conclusive.

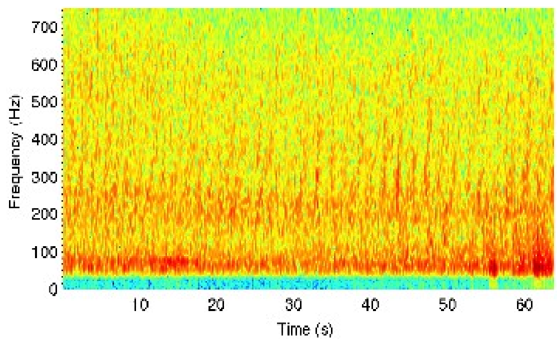


Figure 11. Spectrogram measurement at a distance of 128 meters, showing the variation of frequency components in the range 50 Hz - 750 Hz over time.

6 ACKNOWLEDGEMENTS

This research is part of the R&D project, Wind & Biodiversity, co-financed by the national program of incentives for the Portuguese businesses and industry QREN (in the scope of its R&D incentive program), under the operational program Mais Centro, and with the support of the European Regional Development Fund. The authors would also like to thank Iberwind, developer of the Serra dos Candeeiros wind farm.

REFERENCES

[1] L. Rodrigues, L. Bach, L. Biraschi, M. Celuch, and M.-J. Dubourg-Savage, “Report of the IWG on Wind Turbines and Bat Populations,” in *4th Meeting of the Standing Committee - Eurobats*, 2010.

[2] C. Long, J. Flint, P. Lepper, and S. Dible, “Wind turbines and bat mortality: interactions of bat echolocation pulses with moving turbine rotor blades.,” in *Fifth International Conference on Bio-acoustics 2009*, 2009, vol. 31, no. 1, pp. 183 – 190.

[3] J. Kerns and P. Kerlinger, “A study of bird and bat collision fatalities at the Mountaineer Wind Energy Center, Tucker County, West Virginia: Annual report for 2003,” 2004.

[4] E. B. Arnett, Iw. P. Erickson, J. Kerns, and J. Horn, “Relationships between Bats and Wind Turbines in Pennsylvania and West Virginia : An Assessment of Fatality Search Protocols, Patterns of Fatality, and Behavioral Interactions with Wind Turbines,” 2005.

[5] J. K. Fiedler, “Assessment of Bat Mortality and Activity at Buffalo Mountain Windfarm, Eastern Tennessee,” University of Tennessee, USA, 2004.
[6] D. R. Griffin, “The importance of atmospheric attenuation for the echolocation of bats (Chiroptera),” *Anim. Behav.*, vol. 19, no. 1, pp. 55–61, 1971.
[7] J. W. Horn, E. B. Arnett, and T. H. Kunz, “Behavioral Responses of Bats to Operating Wind Turbines,” *J. Wildl. Manage.*, vol. 72, no. 1, pp. 123–132, 2008.
[8] C. V Long, J. Flint, and P. Lepper, “Wind turbines and bat mortality: Doppler shift profiles and ultrasonic bat-like pulse reflection from moving turbine blades,” *J. Acoust. Soc. Am.*, vol. 128, no. 4, pp. 2238–45, Oct. 2010.
[9] J. M. Szewczak and E. B. Arnett, “Ultrasound emissions from wind turbines as a potential attractant to bats: a preliminary investigation,” USA, 2006.
[10] H. Fletcher, *Speech and Hearing in Communication*. NY: Acoustical Society of America, 1995.
[11] C. on E. I. of W. E. P.-N. R. Council, *Environmental Impacts of Wind-Energy Projects*. The National Academies Press, 2007.