Department of Aeronautical and Vehicle Engineering

MWL The Marcus Wallenberg Laboratory for Sound and Vibration Research

Directivity of sound from wind turbines

A study on the horizontal sound radiation pattern from a wind turbine

Manne Friman

Stockholm, 2011
Thesis for the degree of Master of Science, 30 Hp
Department of Aeronautical and Vehicle Engineering
The Marcus Wallenberg Laboratory for Sound and Vibration Research

Supervisor:
Karl Bolin, KTH, Department of Aeronautical and Vehicle Engineering
Assistant supervisor:
Martin Almgren, ÅF-Sound and Vibration
Paul Appleqvist, ÅF-Sound and Vibration
Examiner:
Hans Bodén, KTH, Department of Aeronautical and Vehicle Engineering

Abstract

In the present paper, a study on the directivity of sound from a wind turbine has been conducted. The aim of the study is to investigate the horizontal sound radiation pattern through a field study compared to a noise prediction. The benefit of the results may be used to optimize the output effect from the wind turbine while the guidelines for noise levels at nearby residential areas still are met.

The complete directivity pattern around the wind turbine was investigated by performing emission measurements around the wind turbine from a method described in IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique.*
Furthermore, the dominant sound source from the wind turbine, the turbulent boundary layer trailing edge noise, and the frequency range where it is dominating has also been scrutinized.
The results show that the dipole character of the trailing edge noise has an impact on the entire horizontal radiation pattern from the wind turbine.

From a field study it was found that there was a distinguishable directivity of the sound.
On a distance of 125 m from the wind turbine the sound pressure level in the crosswind direction of the wind turbine is close to 3 dBA less than the sound pressure level in the downwind direction of the wind turbine when the wind speed is 8 m/s at a height of 10 m. The difference between other directions compared to the downwind direction is less significant.
This could be utilized to optimize the power output, however the difference in sound level is relatively small but the advantage for power output have to be quantified before a conclusion of the benefits can be made.

Keywords
Directivity, wind, turbine, noise

Sammanfattning

I föreliggande rapport, har en studie om ljudets direktivitet från vindkraftverk utförts.
Syftet med studien är att undersöka den horisontella ljudutstrålningen genom en fältstudie som jämförs med en prediktion av bullernivån. Resultatet kan möjligtvis användas för att optimera den producerade effekten från vindkraftverk samtidigt som riktlinjerna för bullernivåerna vid närliggande bostadsområden hålls uppfyllda.

Ljudets direktivitet runt vindkraftverket undersöktes genom att utföra emissionsmätningar runt vindkraftverket med en metod som beskrivs i IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique.*
Den dominerande ljudkällan från vindkraftverket är ljudet som uppstår nära rotorbladets spets när turbulens som uppstår längs med rotorbladet rör sig över bladets bakkant (*Turbulent boundary layer trailing edge noise*). Frekvensområdet där det ljudet dominerar har undersökts noggrant på grund av ljudets starka direktivitet och att det är den dominerande ljudkällan från moderna vindkraftverk.
Resultaten visar en direktivitet av dipolär karaktär vilket tyder på att ljudet som uppstår vid bladets bakkant har en inverkan på hela det horisontella ljudutstrålningsmönstret från vindkraftverket.

Från en fältstudie fann man att det fanns en tydlig direktivitet på ljudet.
På ett avstånd av 125 m från vindkraftverket var ljudtrycksnivån i sidvinds riktning av vindkraftverket nära 3 dBA lägre, när vindhastigheten var 8 m/s på 10 meters höjd, än ljudtrycksnivån var nedströms om vindkraftverket i vindriktningen.
Skillnader mellan andra riktningar jämfört med nedströms om vindkraftverket är mindre signifikanta.
Detta skulle kunna användas för att optimera effekten, dock är skillnaden i ljudnivån relativt liten men fördelen som kan göras i uteffekt kan inte uteslutas innan den blivit kvantifierad.

Sökord
Direktivitet, vindkraft, buller

Acknowledgements

During the spring 2011, the present thesis was performed and I would like to thank techn. Dr. Martin Almgren for the opportunity to conduct the thesis at ÅF - Sound and vibration.

I would like to extend a special thanks to my supervisor techn. Dr. Karl Bolin at the Department of Aeronautical and vehicle engineering at the Royal technical high school. I am grateful for his guidance and support.

I would also like to give special thanks to my supervisor Paul Appelqvist at ÅF- Sound and vibration. Your help and consultancy have been much appreciated in the pursuit of this thesis.

The field study was conducted in collaboration with Hans Klingberg, another student that was performing his master thesis at ÅF – Sound and vibration I would like to thank him for the discussions and conclusions we came to when facing problems in our thesis work and also his help with the noise prediction simulation.

Finally, I would like to thank the rest of employees at ÅF - Sound and vibration, who have helped me with various matters during the spring and been very welcoming.

Stockholm, May 2011-05-24

Manne Friman

1 Introduction

1.1 Scope

Wind turbines are an environmentally friendly and renewable source of energy, which are two important factors for the future of energy production. But the noise from wind turbines is often perceived as annoying and affects residents in the vicinity.
The guidelines for which sound pressure levels from wind turbines that are allowed varies between countries, but is a main concern for manufacturer, owner and people living nearby the wind turbine.

A guideline issued by the Swedish National Environmental Protection Agency (*Naturvårdsverket*) states that the noise levels at the facades on buildings of nearby residential areas should be below 40 dB(A) when the wind speed is 8 m/s at 10 meters height [1].

Relevance: A way to ensure that this guideline is followed is to calculate a prediction on how the noise will affect the surrounding area around the wind farm before construction and then follow up by performing emission or imission measurements to investigate the sound power level that the wind farm emits. The results of these predictions and measurements can then be used to support the building permits or be used to determine how much the wind turbine will be allowed to be active. Therefore sound propagation is an important part when planning construction of wind turbines

However, the sound from wind turbines is not radiating equally strong in all directions propagating away from the wind turbine. There are actually several sound sources with different characteristics of both tone and sound radiation pattern.
When measurements of sound from wind turbines are performed, one of the most important parameters is the sound power level, which is the acoustic power radiated from the source.
This is measured downwind of the wind turbine, assuming that the sound comes from an omni-directional point source. This means that directivity is neglected.
Sound power level is measured in accordance with standard IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique* [2]. The standard includes an option to measure how the noise level varies in different directions from the sound source.
This is performed to determine the sound radiation pattern also known as directivity of the sound.

Benefits: By knowing how the sound radiates from a wind turbine, one can regulate the turbines setup depending on directivity and direction to nearby residential areas to optimize power output while still fulfilling the conditions in different guidelines.

1.2 Objectives

The objectives of this master thesis are to:

- Investigate how the sound pressure level varies in different directions from the wind turbine and what the consequences may be.

- Program a prediction code for the sound radiation pattern to compare with measurements.

- Discuss how the sound radiation pattern can be used to optimize the power output from a wind turbine while keeping the sound level to the limit of 40 dB(A) at the facades on buildings of nearby residential areas.

1.3 Limitations

The study has been limited to certain restrictions:

- This thesis is focusing on horizontal directivity, which is according to the measurement method described in standard 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique*s. Vertical directivity is not included in the field study.

- Results of the measurements will be limited to one wind turbine and to the parameters that apply in that specific time, such as turbine mode, angle of attack and rotation speeds, temperature, wind speed, surrounding environment, season specifics instead of a general view over the year.

- The measurements are limited to a shorter time-span during daytime, thus variations during the day, such as stratification of temperature could not be observed. However a measurement during night was also performed so the comparison between day and night is conducted.

- Directivity is frequency dependent and the perceived loudness of the sound source will vary with the distance between observer and blade. However, in this study the total noise will be investigated which means a minute average of the equivalent sound pressure level covering several revolutions of the rotor will be studied.

- The wind turbine noise prediction is limited to turbulent boundary layer trailer edge noise which is the dominant sound source of a wind turbine and optionally separation stall noise.

1.4 Text outline

This is a brief description of the text outline of this master's thesis report

Chapter 2 Theory: Fundamentals of theory on sound and theory about acoustics from wind turbines.

Chapter 3 Method: A description of the methods used for this study.

Chapter 4 Field study: The measurement setup is described and the object investigated.

Chapter 5 Analysis of field study: Analysis of data and a comparison between prediction and results.

Chapter 6 Discussion: Reflections about the results, analysis and the methods used in this study.

Chapter 7 Conclusion: Summary of the study and in short what could be concluded from the analysis

Chapter 8 Future work: Implementation of the conclusion in future design of wind farms.

Chapter 9 References: List of the sources of information that have been used in this study.

2 Theory

This chapter intends to give some perspective about sound from wind power. It describes the fundamental acoustic, sound sources, different parameters that can affect the sound, measurement methods used to observe sound and important information from the literature study.

2.1 Fundamental acoustics

The unit used to measure sound is called Bel. It is a value based on a ratio between a power and the reference value of that powers unit. In acoustics, Bel is too large of a unit and instead you use a tenth of a Bel called decibel according to *och vibrationer (Sound and Vibrations)* [3].

The most common ways to measure sound is based on either changes of pressure in the air, the intensity of particles in the air or the total acoustic power.

The human ear can hear frequencies between 4Hz and 20 kHz. In order to mimic the ear's perception capabilities, a filter that reduces the influence of low frequencies can be used. The most common filter to use is A-weighting, with the unit dB(A), but there are also B and C-weighting [4].

2.1.2 Sound power Level

Sound power level is a unit which is used to obtain the acoustic power radiated from a sound source. The instantaneous acoustic effect that propagates through a surface S with the normal vector n according to *Ljud och vibrationer (Sound and Vibrations)* [3] is defined as:

$$W(\vec{r},t) = \int_s p(\vec{r},t)\vec{u}(\vec{r},t)\vec{n}dS \quad \text{[W]} \tag{2}$$

Equation 2: Sound power level

Where

$W(\vec{r},t)$	is instantaneous acoustic effect [W].
$p(\vec{r},t)$	is the sound pressure [Pa]
$\vec{u}(\vec{r},t)$	is the particle velocity [m/s]

From this basic mechanical formula the sound intensity and sound pressure level can be derived. Equation 2 and 3 are obtained from *Ljud och vibrationer* [3].

$$\tilde{p} = \sqrt{\rho_0 c\overline{W} \,/\, 4\pi r^2} \quad \text{[Pa]} \tag{3}$$

Equation 3: Sound pressure level

Where

ρ_0	is the reference density of air [kg/m^3].
c	is the speed of the sound [m/s].
$\overline{W}$	is the time averaged sound effect level [W].
r	is the distance between the sound sources to the observer [m].

These units are the most common when quantifying sound.

2.1.3 Sound propagation

The sound pressure level decrease when sound propagates through the atmosphere, because the sound energy is distributed in a wider area. This is known as geometric dispersion.
The spherical spreading of the sound pressure level is reduced by 6 dB(A) as the distance is doubled. Sound propagation is affected by wind and air temperature which varies with height and the ground damping influence and roughness [3].

2.1.4 Directivity of sound

The directivity of sound means that the sound level emitted from a source varies in strength depending on the different directions from the sound source.
Thus, the sound has a directional component and consequently a sound source can be considered as omni-directional or directional according to Vargas [5].

If the sound is directional, the strength of the noise level may vary in different directions from the sound source, this can be represented as a pattern of sound radiation, also called the directivity of the sound. If it is omni-directional, the sound source radiates energy equally in all directions.

Directivity is measured in either a Directivity index in decibels or as a dimensionless value Q.
An example of an omni-directional source would be a balloon that pops, it emits sound equally in all directions. This represents a Q value of 1.
Another example of directivity of sound is when you try to be heard at long distances outside and you cup your hands around your mouth to increase the directivity. This increases the Q value.
In this study, aerodynamic sources from the rotor blades are mainly investigated and these sources which are induced by flow are expected to have a dipole character of directivity.

In the standard IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique* [2] a method to describe the directivity of the sound is the directivity index.
This method evaluates the difference in sound pressure level between the measurement points by comparing the sound pressure levels with the reference point and accounting for different distance.

$$\Delta i = L_{Aeq,i} - L_{Aeq,1} + 20\ Log\left(\frac{Ri}{R1}\right) \quad [dB] \tag{3}$$

Equation 3: Directivity Index

Where

$L_{Aeq,i}$ is the A-weighted sound pressure level at the positions 2, 3, 4, 5 or 6 corrected for background noise in the same position.

$L_{Aeq,1}$ is the A-weighted sound pressure level at reference position 1, measured simultaneously with $L_{Aeq,i}$ and also corrected for background noise.

R_i is the slant distance between the rotor centre and positions 2, 3, 4, 5 or 6 and

R_1 is the slant distance between the rotor centre and reference position 1 [2]

2.1.5 Lighthill's equation

To explain aerodynamic noise which is sound generated by flow a formula containing the classical wave equation (left hand side of eq.4) together with the flow induced source term (right hand side of eq.4) is used. This formula is better known as Lighthill's equation according to Lighthill [6].

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial\tau^2} - \nabla^2\right)p = \frac{\partial^2 \rho_0 u_i u_j}{\partial x_i \partial x_j} \tag{4}$$

Equation 4: Lighthill's equation

Where

c	is the speed of the sound [m/s]
∇^2	is the nabla operator which in Cartesian system equals $(\frac{\partial}{\partial x_1}, \frac{\partial}{\partial x_2}, \frac{\partial}{\partial x_3})$
x	is a Cartesian co-ordinate
u	is the flow velocity for i,j=1, 2, 3. The factor between u_i,u_j is called Lighthill's turbulence stress tensor which is important in the generation of noise that is dependent on the flow conditions considered. [6]

For a wind turbine, which has rotating blades with solid surfaces and sharp trailing edges the source term can be modified according to reference [7]. Due to the motion of the rotor the sound generation will also be modified with a Doppler-shift that modifies the frequency and can also cause changes in the directivity according to Howe [8].

2.2 Noise from wind turbines

2.2.1 Aerodynamic noise

Aerodynamic noise is generated when the rotor blade passes through the air according to Wagner [9] As the blade moves the sound source form a dipole characteristic of directivity around the blade. The sound is perceived as a swishing or hissing sound and is of broadband character [5].
For the modern wind turbines it is normal that the aerodynamic noise generated at the blades is the dominant sound from the wind turbine and these sounds are described by Lighthill's equation.
The impact of noise characteristics is the angle of attack, blade shape, blade tip velocity and turbulence in the air [5]. The dominant aerodynamic noise from the blades is seen in Fig.1 from [10].

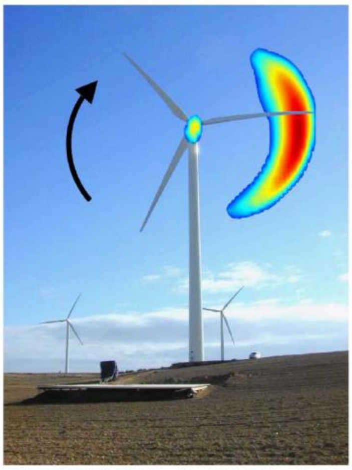


Fig.1. The dominant sound source as pictured by an acoustic camera [10]

2.2.1.1 Airfoil self-noise

The dominating sound source from a wind turbine is the aerodynamic sound sources.
The airfoil self-noise that is most prominent is the trailing edge noise pictured in Fig.2.
The noise originates from the interaction between turbine blade and turbulence from its own boundary layer and wake, it is generated when the boundary layer moves over the trailing edge [4]. As described in figure 2 [5], the scattering from the vortical disturbances on the boundary layer propagates (from left to right in fig.2) into acoustic waves at the trailing edge of an airfoil which causes turbulent boundary layer trailing-edge noise (TBL-TE) [5].

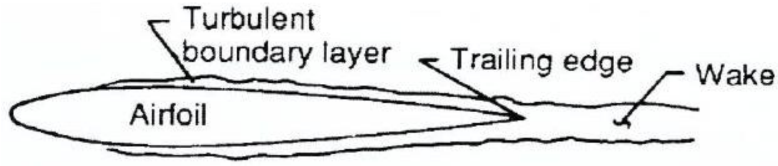


Fig.2. Sources for aerodynamic noise at the airfoil [5]

The TBL noise is also seen as a prominent source of noise by the acoustic camera in figure 1.
The dominant sound originates close to the tip, but not at the very edge. According to Oerlemans [10, 19] practically all downward radiated blade noise is produced on the blades downward movement. There are several other aerodynamic sound sources that origin at different locations of the blade. Such as separation-stall noise, tip vortex formation noise and vortex shedding from the laminar boundary layer according to Vargas [5]. However, in this study the main focus is on trailing edge noise and in some extent separation-stall noise for high angles of attack of the blade.

2.2.1.2 Inflow turbulence noise

Low frequency noise due to inflow turbulence occurs because of modulations in the lifting force of the blade. The reason for this is the incoming turbulence which causes changes in flow speed and angle of attack. Inflow turbulence can also be the source of higher frequency noise if there is an interaction between turbulence and the leading edge according to Lowson [11].

2.2.1.3 Low frequency noise from aerodynamic sources

If the rotor is positioned downwind of the tower, it creates a strong low-frequency thumping sound when the blade passes the tower. Wind turbines with the rotor positioned downwind are very unusual in the current situation [11].

2.2.2 Mechanical noise

The mechanical noise is not as noticeable as the aerodynamic noise from modern wind turbines because the sound insulation of the mechanical components of the assembly is highly developed. However, there can be failure or wear of the gear and fittings which can cause a tonal sound [11].

2.3 Environmental effects

The environmental effects may have great influence on the results of a measurement.
The right wind speeds, weather conditions and amount of background noise is required for a standardised measurement according to the standard [2].
The measurements that have been performed for this study were emission measurements, as the distance between point of measurement and sound source is relatively short compared to an imission measurement. Therefore the environmental effect is not as prominent as it would have been for an imission measurement.

2.3.1 Refraction
The phenomenon that sound waves can change direction in different ways depending on environmental effects mentioned in 2.3.2 and 2.3.3 is called refraction. Refraction is affected by the speed of the sound which is influenced by both wind speed gradient and temperature gradient [12]. The temperature gradients effect on the sound waves described in 2.3.2 are shown in figure 3 [13].

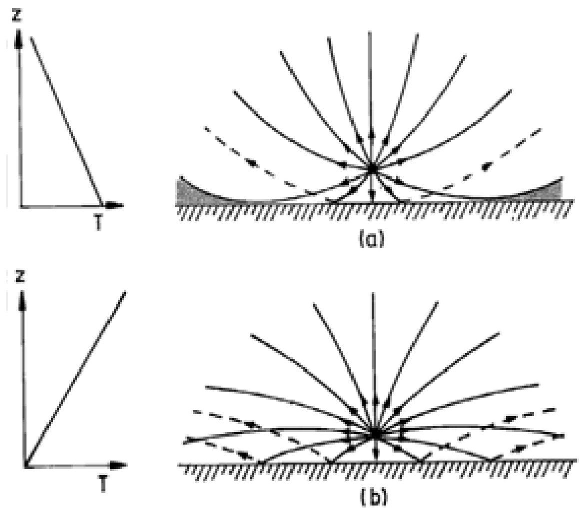


Fig.3. The refraction of sound waves due to refraction at (a) positive temperature gradient and (b) negative temperature gradient [13].

2.3.2 Wind speed gradient
The wind speed gradient is the variation of wind speed depending on altitude.
As the wind gets closer to the ground and gets reflected and absorbed by the ground surface, the wind speed is slowed down by the ground roughness. The wind speed may also increase in speed due to layers of air with relatively high temperature.
For sound propagation downstream of the wind turbine, the wind speed will be added to the sound waves normal propagation speed.
A high ground roughness will cause higher wind speed gradient. The increase of gradient will cause the sound waves to refract downward towards the ground when propagating downstream.
Upstream of the wind turbine, the sound waves will refract up, which causes the sound waves to hit the ground surface with a flat angle, increasing the magnitude of the ground attenuation.
Due to this, one can expect lower sound levels upstream than downstream.
There might even be a sound shadow which damps the sound even further according to the report from *Naturvårdsverket* [13]. Examples of these two phenomena can also be seen in figure 4 [14].

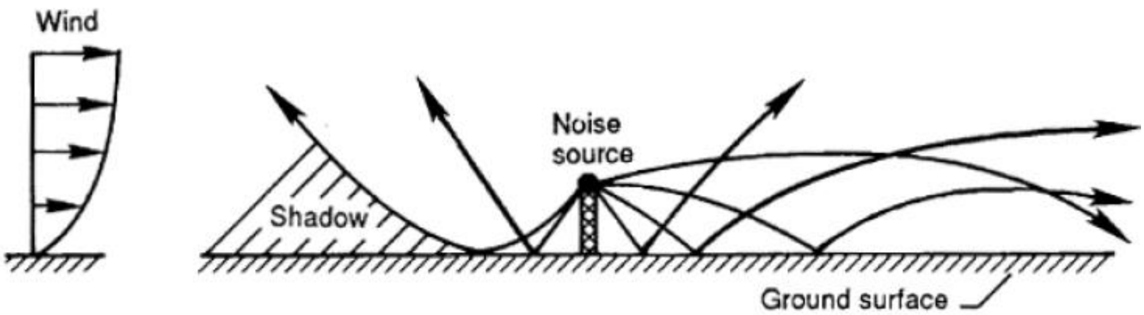


Fig. 4. The sound propagation around a wind turbine with the presence of a wind speed gradient *[14]*

2.3.3 Temperature gradient
Temperature varies with height over ground due to the suns height over the horizon and the amount of cloudiness. With increasing temperature the speed of sound is also increased [13].

A negative temperature gradient is when the air temperature will decrease with height over ground. This occurs for example on clear days and will cause the sound waves to refract upwards which in turn causes decreased of the sound levels as one move away from the sound source.
Furthermore a negative temperature gradient correlates to high wind speeds at ground level, high turbulence factor and low vertical wind gradient [13].

A temperature inversion is when the air temperature increases with height over ground.
This happens on a clear night when the wind is still and will cause the sound waves to refract downwards which in turn could cause the sound to be audible on long distances.
Furthermore a temperature inversion causes low wind speeds at ground, low turbulence factor and high vertical wind gradient [13].

At certain circumstances, there may be height inversion, where the temperature decreases with height at first, and then starts increasing through a higher air layer. If this occurs, sound waves can propagate over large distances with little damping [13].

The wind is influencing the sound from wind turbines more than temperature, and the influence of the temperature gradient is mainly when the wind speed is low [13].

2.3.4 Air absorption
The air absorption is influenced by frequency, humidity, air pressure, distance between source and receiver and temperature. The air absorption has greater effect for sound with high frequency and long propagation distances according to the report by *Naturvårdsverket* [13].

The air absorption is not accounted for in IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique* [2]. This will cause the sound power level at frequencies over 1 kHz to be underestimated. However, the difference is less than 1 dB for A-weighted sound power level [15].

2.6 Background noise
When measuring sound from wind turbines, it is required to separate the background noise from the wind turbines noise according to the standard [2]. This means all the wind turbines in the vicinity have to be parked to focus and measure the sounds that take place at the location in exception of the wind turbines.

Background noise is divided into two subcategories, firstly natural background noise such as wind, animals, waves and noise from vegetation and secondly community noise such as traffic and industries according to Appelqvist [16].

Background noise varies during the day and due to the temperature inversion in the evening the wind speed at ground is decreased which also decreases the background noise which in turn give rise to a more prominent wind turbine noise as it is less masked according to Appel [17].

2.7 Measuring methods

2.7.1 Noise emission

To measure noise emission of a wind turbine, the method described in 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique*s [2] is the preferred course of action. [2]
Measurements are performed at a distance from the base of the wind turbine which is equal to the height plus the radius of the rotor. The microphone is placed upon a measuring board lying on the ground. The reason is to minimize the wind induced noise and to create a uniform reflection from site to site due to the acoustically hard surface of the ground board.
The reflections from the ground are also negligible so the ground effect is not taken to consideration.
The measurement point should be downstream of the wind turbine in the direction of the wind and it is optional to add three more measurement points in other directions to determine directivity.
By following this procedure the sound power level can be determined in relation to different wind speeds. [2]

2.7.2 Noise imission

Noise imission measurement should simulate the sound pressure level at the point of the receiver i.e. the facades of nearby buildings. When measuring noise imission, the wind turbine noise is treated as community background noise. Therefore measuring noise imission of a wind turbine is more complex than noise emission, because the natural background noise can be difficult to distinguish from the wind turbine noise. For both emission and imission there may be noise generated by wind at the microphone, sound induced from wind flowing through adjacent trees, traffic, aircrafts, industries, animal or human activities and streams or waves. [2]
However, for imission measurements which are further away from the wind turbine, the sound pressure level from the wind turbine can be exceeded by the background noise.

2.8 Wind turbine structure

A wind turbine can be divided into five major parts according to Vargas [5]. This can be seen in fig. 5.

1. **Rotor blades:** Usually there are 2-3 blades equally distributed over the rotor plane.
2. **Hub:** The center of the rotor which connects the blades and the main shaft.
3. **Nacelle:** Contains all the electrical apparatus where mechanical energy is converted to electrical.
4. **Tower:** Supports the nacelle and the thus the blades.
5. **Ground foundation:** A structure of reinforced cement built deeply into the ground. [5]

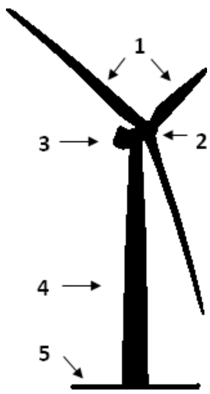


Fig.5. Wind turbine structure

2.9 Wind turbine noise prediction

A wind turbine noise prediction for aerodynamic sound sources have been implemented to compare the experimental results with simulations performed in Matlab® (Appendix D). The sound sources that have been accounted for in the prediction code are the aerodynamic sources from the blades. The simulation is based on a code from the report *Airfoil self-noise and prediction* [18].

The simulation is a simplified noise prediction where the directivity functions for the trailing boundary layer noise for high frequencies eq.5 and optionally low frequencies eq.6 have been calculated. The turbulent layer trailing edge noise and separation stall noise have identical scaling laws [5]. However, for separation stall noise eq.6 should be used for the directivity factor.
In equation 5, (θ_e, Φ_e) corresponds to the observer positions around the wind turbine.

The sound pressure levels for suction side and pressure side have been calculated according to equation 7, 8 and 9 over a revolution of the rotor for one blade and are then multiplied for the number of blades. The dimensions of the wind turbine, general environmental conditions and mean wind speed from the field study have been implemented in the simulation.

Limitations:
The noise prediction is theoretical and will over estimate the attenuation in crosswind plane.
In reality, the sound pressure level will not decrease as much as predicted because other sound sources such as background noise and mechanical noise will still be present.
In the reports described in 2.10.3 and 2.10.5 the theoretical decrease in the crosswind have been adjusted with and overridden, adjusting the observer position to a location not critical for eq.5 and 6.
The simplification that has been included is a general background sound source that increases the overall sound pressure levels, causing the crosswind decrease to be more realistic seen in Fig. 6a, 6b
The blades have been divided into segments, however the sound sources have not been applied to the actual segment where the sound source originates. Equations 5 to 10 are found in [5].

$$\overline{D_h}(\theta_e, \Phi_e) \approx \frac{2\sin^2(\theta_e/2)\sin^2\Phi_e}{(1+M\cos\theta_e)[1+M-Mc)\cos\theta_e]^2} \qquad (5)$$

Eq. 5. Directivity function for high frequency TBL noise [5]

$$\overline{D_l}(\theta_e, \Phi_e) \approx \frac{\sin^2(\theta_e/2)\sin^2\Phi_e}{(1+M\cos\theta_e)^4} \qquad (6)$$

Eq. 6. Directivity function for low frequency TBL noise [5]

$$SPLp = 10\log\left(\frac{\delta_p{}^* M^5 L\overline{D_h}}{r_e{}^2}\right) + A\left(\frac{St_p}{St_1}\right)) + (\mathrm{K1}-3) + \Delta\mathrm{K}_1 \qquad (7)$$

Eq. 7 Sound pressure level from TBL-TE noise from pressure side of blade [5]

$$SPLs = 10\log\left(\frac{\delta_s{}^* M^5 L\overline{D_h}}{r_e{}^2}\right) + A\left(\frac{St_s}{St_1}\right)) + (\mathrm{K}_1-3) \qquad (8)$$

Eq. 8 Sound pressure level from TBL-TE noise from suction side of blade [5]

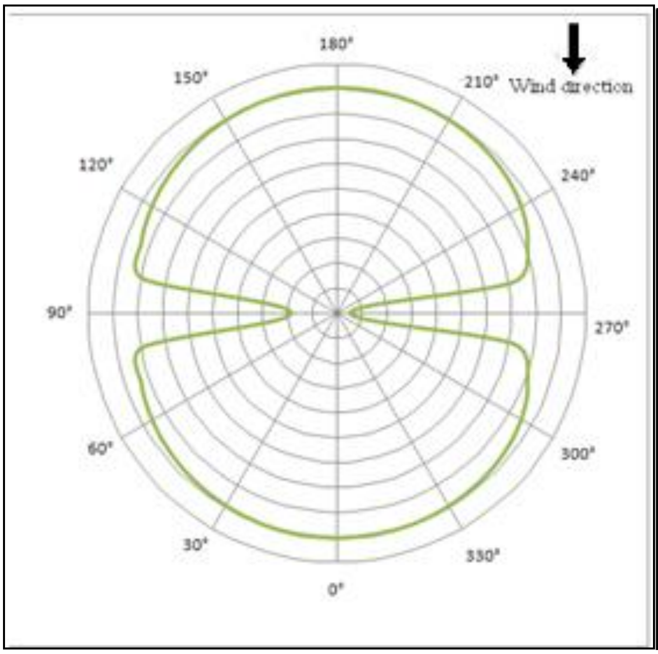
$$SPL_\propto = 10\log\left(\frac{\delta_s{}^* M^5 L\overline{D_h}}{r_e{}^2}\right) + B\left(\frac{St_p}{St_1}\right)) + \mathrm{K}_2 \qquad (9)$$

Eq. 9 Sound pressure level from separation stall noise from suction side of blade [5]

$$SPL_{TOT} = 10\log\left(10^{SPLp/10} + 10^{SPLs/10} + 10^{SPL\alpha/10}\right) \quad (10)$$

Eq. 10 Total Sound pressure level combined from equation 7,8 and 9 [5]

Where M is the Mach number, St is the Strouhal number, δ^* is the displacement thickness, A, B, K1, K2 are amplitude factors, re is the distance to the observer. For information and units see Appendix D



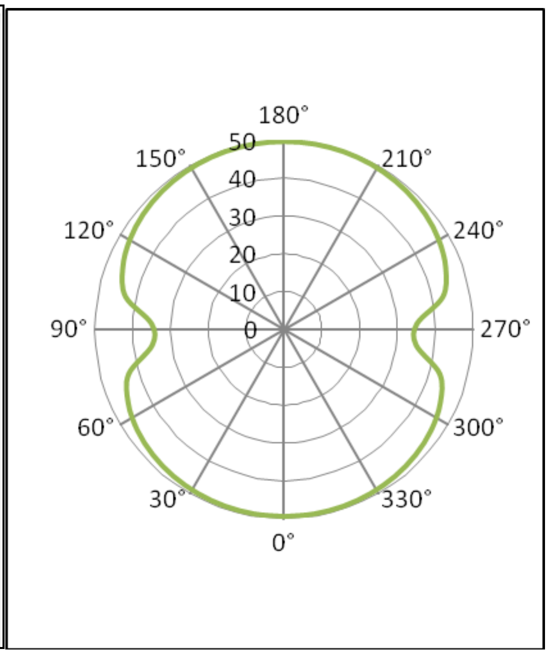


Fig. 6a. Predicted directivity of a wind turbine

Fig. 6b. Sound source added to *Fig.6a*

2.10 Literature study

2.10.1 Method for literature study

In the beginning of this master thesis a literature study was performed to achieve the knowledge required. The focus of the literature study was on the sound propagation of noise from wind turbines, wind turbine noise predictions, directivity of different sound sources and measurement methods for wind turbines.

The literature included relevant standards, project reports about the topic, reports including directivity and semi-empirical methods for evaluation of vertical directivity.

2.10.1.1 Query method

In search of literature in the field, material has been found through searches in technical databases. Particularly ScienceDirect, Scopus, ETDE, Web of Science, Compendex, NTIS and Inspec have been used. Even Internet-based search engines have been used to some extent.

2.10.2 Conclusion of literature study

The conclusion that can be drawn from earlier work about directivity of noise from wind turbines states that there is a reduction of sound radiation in the crosswind direction in comparison to the other directions from the wind turbine. Measurements upstream of the tower against the wind direction also tend to have lower sound levels compared to the downstream measurement point due to refraction.

To give an insight on the problem the following chapters are summaries of earlier work in the field.

2.10.3 Prediction of wind turbine noise and validation against experiment, S.Oerlemans

In report [10] a semi-empirical prediction method for trailing edge noise from wind turbines has been tested. The prediction code that needs the blade geometry and the turbine operating conditions was compared to measurements by an acoustic array and directivity measurements and the prediction showed the same characteristics as the results of the measurements.

The report shows that noise that is emitted to the ground was produced when the blade of the rotor was moving downward. This is due to trailing edge noise directivity and convective amplification.
By applying the prediction code to calculate noise footprints, it is shown that for cross-wind directions the average level is lower than in upwind and downwind directions.

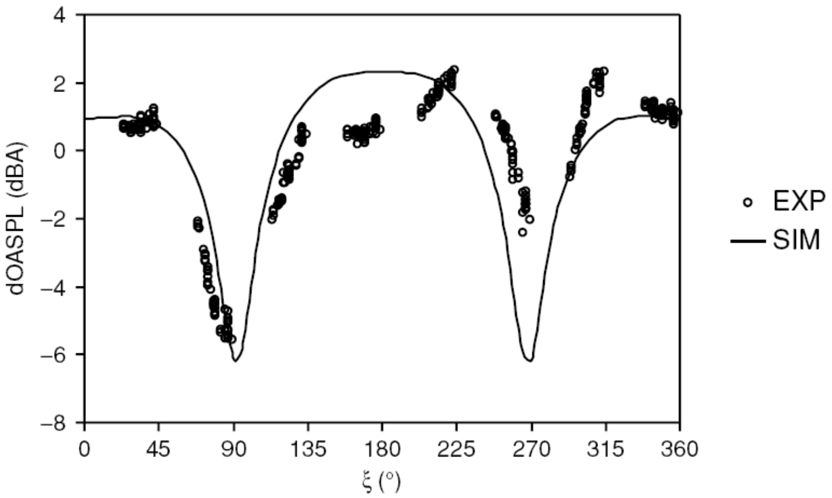


Fig. 7. Measured and predicted directivity of a wind turbine [19]

In figure 7 from *Location and quantification of noise sources on a wind turbine* [19] the directivity in the far field for a wind turbine is shown with sound pressure levels relative to the reference point as a function of observer location.

The figure shows how the overall A-weighted sound pressure level summed between 250-800 Hz is different depending on the angle that one is facing the wind turbine.
The frequency range is chosen to 250-800 Hz because the trailing edge noise is located in the same frequency range. This study shows that acoustic measurements on a circle around the turbine constitute a measurement of the complete trailing edge noise directivity function, including directions outside the plane normal to the trailing edge.

There are eight clusters of experimental values with the angle depending on the angle between the measurement position and the direction that the wind turbine rotor is pointing.
The yaw angles are clustered because measurement positions are fixed while the yaw angle changes to align the blades perpendicular to the wind direction.

It is apparent that the experimental values are fitting the simulated values and that there is a difference of 8 dB depending on direction.
The reason that the upwind sound levels are slightly higher is because of the convective factor in equation 7 (Chapter 5, p.10). This is because when the blade azimuth angle is 90° the inverted blade flow velocity points upwind.

2.10.4 Low frequency noise-sound power measurement method, B. Søndergaaard

In the report Noise Sound power measurement method from DELTA a measurement of directivity according to 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique*s have been performed.

This report mentions vertical directivity on a 22 m high wind turbine from a measurement made by DELTA, where it was up to 5 dB difference in an octave band. The highest sound power levels were measured between 30° and 50° in angle of attack between measurement point and sound source. The report also states that air absorption may affect up to 1 dB on the A-weighted sound power level at frequencies over 1 kHz. [15]

In the report it is concluded that directivity is calculated to be low at low frequencies on new wind turbines due to high wave length. If the purpose of the measurement is to investigate how the nearby residential areas are affected then measurement according to standard [2] are acceptable but a secondary wind screen should be included if the insertion loss is calculated. The report recommends that the reduction of sound power levels over 1 kHz due to air absorption should be included in the calculation [15]. The report also includes a method to calculate insertion loss for secondary wind screen in Appendix A of the report [15]. This method which simulates the inclination angle of a wind turbine have been used for the calibration of the secondary wind screens that were used in the field study of the present paper, with the exception of the reference measurement point.

2.10.5 Wind turbine noise prediction, Luís Filipe da Conceição Vargas

In this report [5], a wind turbine noise prediction method have been developed and compared to other predictions. A problem when developing a prediction code is that the directivity functions approach zero in the crosswind direction of a wind turbine. In order to overcome this unrealistic situation, this method adds a value of 0.2 m to the observer position at 90° and 270° This forces the directivity terms to have higher contribution in the over-predicted values in the rotor plane.

Because the blades are twisted, the dipole pattern of directivity is shaped into a non-symmetric form. This is a consequence of the blade’s pitch which leads the trailing edge backward and the leading edge forward. Furthermore, because the trailing edge is positioned behind the rotor plane the upwind positions will suffer greater noise abatement compare to downwind positions.

Figure 8.a and figure 8.b from reference [5] is an example on how this can change the directivity pattern.

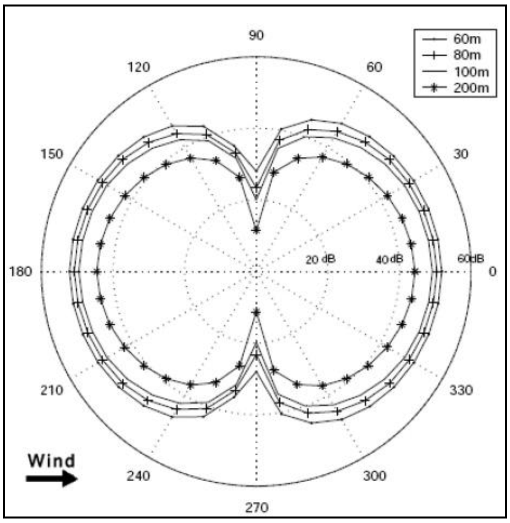


Fig. 8a. Non-symmetric dipole [5]

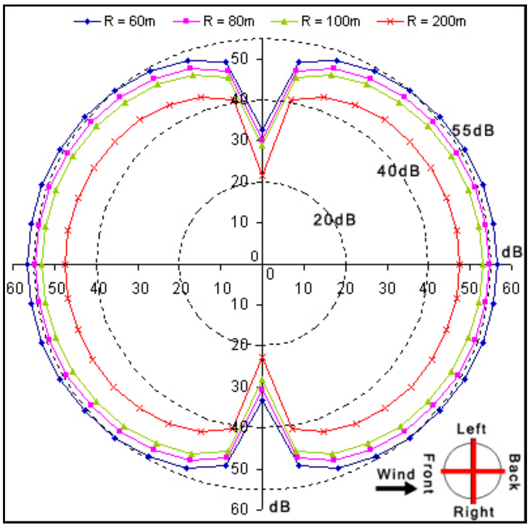


Fig. 8b. Symmetric dipole [5]

3 Method

To determine the directivity a method described in IEC 61400-11 *Wind turbine generator systems – Part 11: Acoustic noise measurement technique* is conducted by placing sound level meters in a circle on the ground around the wind turbine.
By measuring the sound pressure levels at these measurement points at wind speeds in a range considered of interest, and then reducing those levels for the background noise and difference in distance from the sound source, the horizontal directivity can be determined as a comparison between different observer locations. [2]

The measurement setup is according to the emission measurement method described in the standard [2]. An emission measurement is conducted by measuring a sound source on a relatively short distance. The microphone is place on a ground board to create a uniform reflection from site to site due to the acoustically hard surface of the ground board. A primary small wind screen and a secondary larger wind screen are placed upon the microphone to reduced wind induced sound at the microphone.

In addition to the standard measurement setup, two measurement points have been included for the purpose to get higher resolution of measurement point separation in a quarter circles relative to a circle around the wind turbine. The decreased distance between the measurement points relative to the standard setup provides an increased resolution of the directivity pattern.

The measurement points are synchronized with the wind turbine and then the sound pressure levels are recorded every second. These sound pressure levels are then averaged into equivalent sound pressure levels for every minute and then correlated to the wind speed measured with wind mast, anemometer at the wind turbines nacelle and calculation from the power curve of the output effect from the wind turbine. The wind speed is then calculated from the nacelle method and the K-factor method described in the standard [2]. The total noise of the wind turbine is measured with the rest of the wind turbines in the wind farm parked.
The equivalent sound pressure levels are corrected for the background noise at equal wind speeds. To get the correct values at specific wind speed, a regression analysis for the total noise level and background noise is conducted. The background noise at the location is measured with all the wind turbines in the wind farm parked.

During the regression analysis, abnormal sounds are excluded from the data series, such as animal activity, vehicles or other background noises which occurs only in short sessions.
Due to the fact that the measurement points are spread out over a large area, some sound sources may be audible only for one measurement point. For a correct comparison, the third octave bands affected by such noise have been decreased by an amount that is calculated from an average difference between the affected measurement point and the reference measurement point.
To establish the directivity pattern, a comparison between the results from the field study and the predicted values from a simulation is performed for verification.
The simulation is based on a wind turbine noise prediction code from the report Airfoil self-noise and prediction [18] which is the basis of the prediction codes from the reports described in 2.9.3 and 2.9.5. This prediction assumes only aerodynamic noise, which however is the dominating sound source. The simulation which is executed in Matlab® can be seen in Appendix D

4 Field study

To determine the sound radiation in different directions for a wind turbine, the measurement method from standard IEC 61400-11 Wind turbine generator systems – Part 11: Acoustic noise measurement technique [2] was followed.

4.1 Site conditions

4.1.1 Object description

The measurements were performed in a wind farm with several wind turbines.
The turbines that was not target for measurement was parked during the measurement.

Power [MW]	1.8
Hub height [m]	80
Diameter of rotor [m] (D)	90
Wind turbine rotor axis	Vertical
Wind turbine rotor placement	Upwind
Number of blades	3

Table 1. Object description of the wind turbine studied in the field study

4.1.2 Environmental description

Environmental data measured at the time of the field study and roughness length of the ground

Air pressure [hPa]	1026
Relative air humidity [%]	49
Temperature [°C]	10-14
Roughness length, z_0 [m]	0.05

Table 2. Environmental description of weather conditions and ground roughness

4.1.3 Site description

Description of the location for the field study:

Date of measurement	The measurements were performed 2011-03-22 between 14:00 and 16:00.
Topography	Flat farmland with small elevation changes in the terrain in the nearest 1 km.
Type of soil	The ground in the measurement area consists of farmland without crops
Reflecting surfaces	There was no sound reflecting surface around the wind turbine except the ground.
Other sound sources	There were sounds from birds which may have some impact on the results. Sound from vehicles or other irrelevant sounds have been excluded from the results. Furthermore, there was wind induced sound.

Table 3. Description of the surroundings at the site for the field study

4.2 Instruments and equipment

4.2.1 List of Instruments

This is the list of the instruments that were used during the field study:

Instrument term	Product name
Third octave band analyzer	Norsonic 140 and Norsonic 118
Acoustic calibrator, class 1	Brüel & Kjær, type 4231
Distance Meter	Laser meter
Wind and temperature logger	Campbell Scientific CR850 logger, Windsonic wind meter 1405, temperature sensor with radiation screen

Table 4. List of instruments used in the field study

All the instruments have been calibrated according to SS-EN ISO/IEC 17025 the date of calibration can be seen in the instruments log from ÅF- Sound and vibration.

4.2.2 Ground board

On the measurement point a ground board is placed with the microphone placed in the center.
The board should have a diameter of at least 1 m and a thickness of 12 mm according to [2].
The setup can be seen from the field study in fig.9 and according to standard in fig.10 [2].
With the measurement point on the ground, the effects of wind noise and interference phenomena are reduced, but it also means that the vertical directivity cannot be measured.
The sound pressure level shall be adjusted by +6 dB because the surface is acoustically hard. [2]

Fig.9. Measurement setup with ground board, secondary wind screen and sound level meter.

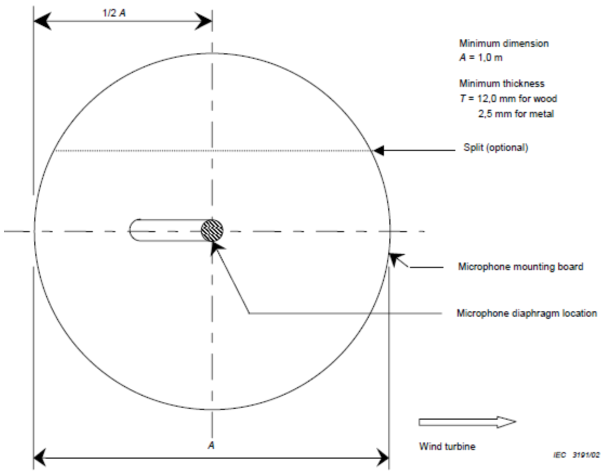


Fig.10. Measurement setup with ground board according to standard. [2]

Furthermore advantages of using a large board are:

- A reduction of the influence of reflected sound from vertical surfaces behind the board.
- Improved signal-to-noise ratio for the ambient sound sources behind the board.
- Improved signal-to-noise ratio due to reduced influence of background noise from turbulent wind around the microphone.

4.2.3 Microphone

The microphone should have a maximum diaphragm diameter of 13 mm.
The tilt angle between the ground board and direction of the microphone against the rotor hub should be between 25 ° - 40 °. This can be adjusted by the distance from the turbine. [2]
These conditions were satisfied during the measurement.

4.2.4 Sound level meter

The sound level meters that were used, Norsonic 140 and Norsonic 118, fulfilled the requirements from the standard [2]. This includes the conditions on microphone membrane and third-octave analyzer.

4.2.5 Windscreen

The windscreen consisted of a half-transparent spherical cell of the foam with a diameter of about 90 mm, which is centered on the diaphragm of the microphone.
A secondary wind screen was placed symmetrically over the smaller windscreen.
The dimensions should be at least a diameter of 450 mm, covered with a layer of open cell foam with a thickness of 13 mm to 25 mm and a porosity of 4 to 8 pores per 10 mm [2].
These conditions were fulfilled for the wind screens used in the field study.
The influence of the secondary wind screen is shown in Appendix C.

4.2.6 Wind mast

The wind mast that was used, *Windsonic wind meter 1405,* fulfilled the conditions in the standard [2]

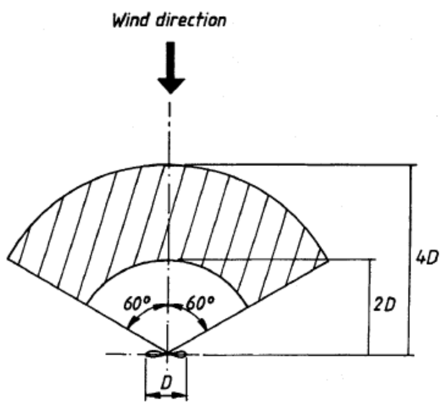


Fig.11. Allowed region for wind mast. [2]

Figure 11 which is from the standard [2] shows the allowed region for the wind mast.
The wind mast was placed in a direct position upwind of the wind turbine, with a distance three times the diameter of the wind turbine rotor away from the tower. This was in the allowed region.

4.2.7 Distance meter

To measure the distance from the measurement points to the wind turbine a binocular laser meter with accuracy according to standard [2]. Distance to base and hub of the wind turbine was measured.

4.3 Measurement method

According to standard [2] the procedure to determine the directivity is to investigate the sound pressure level as a function of wind speed in several measurement points.
The measurement points are placed along a circle with the radius based on the wind turbines dimensions. This is seen in figure 12, which is obtained from the standard [2].
The directivity is determined by measuring the A-weighted sound pressure level and the wind speed simultaneously and then correcting the value for background noise and difference in distance between measurement point and the hub of the rotor. These measurements are then compared with the measurements from the reference measurement point (M1 in Fig.13).

4.3.1 Measurement points

The horizontal distance between measurement point and tower of the wind turbine is recommended to be equal to the hub height plus the radius of the rotor with a tolerance of 20 %.
The inclination angle ϕ between measurement point and hub shall be between 25°-40°. (Fig.14)
The direction of the downwind measurement point should be within ±15° of the wind direction. [2]
Two additional measurement points were included for this measurement, M5 and M6 in fig.13.

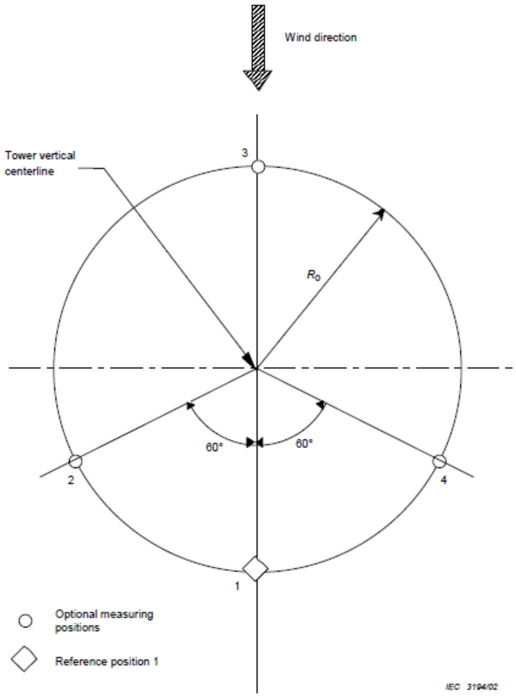


Fig.12. Measurement points from IEC 61400-11 [2]

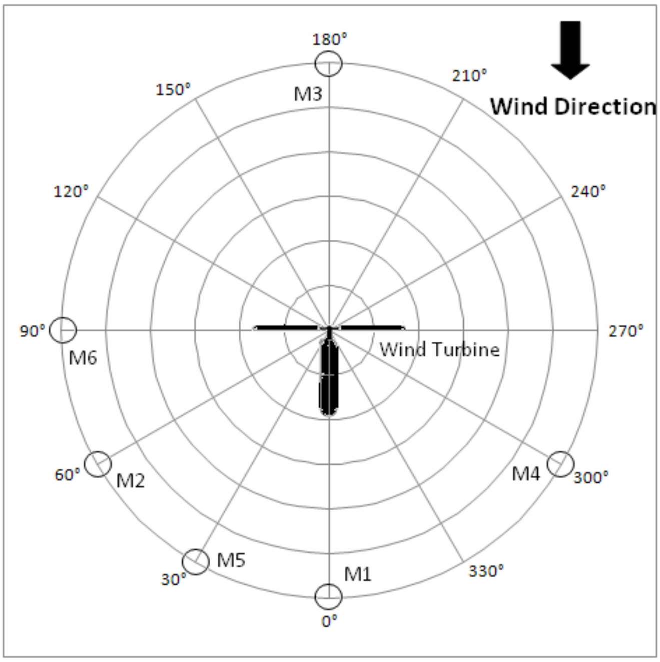


Fig.13. Measurement points used

Measurement points	Distance [m]	
Point abbreviation	***Measurement point to hub (R1)***	***Measurement point to base of tower (R0)***
M1	149	125
M2	132	115
M3	136	114
M4	136	115
M5	137	114
M6	132	113

Table 5. *Distances to measurement points*

The distance between measurement point and wind turbine hub varies due to the slant of the farmland. Furthermore, the distance to reference point is equal to the distance from the ground to the hub plus the radius of the rotor. The other measurement points are closer to the wind turbine. The difference in distance is acceptable according to standard [2] and is corrected for in the results. The slant distance is described in figure 14 which is from the standard [2].

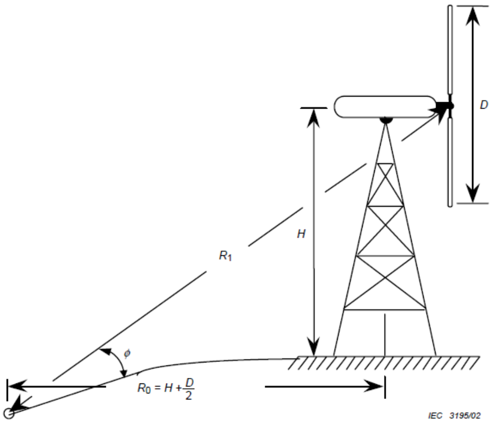


Fig.14. Slant distance, measurement point to hub. [2]

Where

R0	is the horizontal distance between measurement point and tower [m]
R1	is the slant distance between measurement point and hub [m]
H	is the height of the tower [m]
D	is the rotor diameter [m]
ϕ	is the inclination angle between measurement point and wind turbine hub.

4.3.2 Measurement interval and conditions

The measurements of sound pressure level were conducted for wind speeds 6-10 m/s, and the sound pressure level was clustered into integer values of the wind speed.
At least 30 series of measurements with one minute per measurement was required, of these at least three of the measurements shall be within ± 0.5 m / s of each integer of the wind speed. [2]

The background level is measured using the same method as the sound pressure level measurements but with the wind turbine parked. These conditions were satisfied during the measurement.

4.3.3 Frequency range of the different measurements

All measurements were performed with a frequency range of 20-20000 Hz.
The frequency range required for the sound pressure level measurements, both narrowband and octave bands are 50 Hz - 10 kHz according to standard. [2]
Frequency resolution for narrow-band analysis is 2-5 Hz in 2000 Hz and 2-12.5 Hz above 2000 Hz.
Octave -band analysis shall be calculated as the average of the energy level of at least three spectra measured over a minute for each integer wind speed. [2]

4.3.6 Tonality

Tonality is the presence of tones in noise at various wind speeds. The tonality is determined by a narrow band analysis with critical bands according to standard. [2]
This analysis has not been conducted however the term will be used as tones were existent.

4.3.7 Wind speed

Wind speed is measured using two methods. Method 1 calculated from the electrical power output of wind turbine which is directly dependent on wind speed. Method 1 also requires an anemometer at a reference height of 10 m to calculate the background noise. Method 2 is measured with an anemometer height between the base and hub height, and then corrected with respect to the reference height. It is also possible to measure only the hub height and then calculate the wind speed at reference height [2]. The power curve is not from the object studied it is an example of how a power curve for a wind turbine may look like, it is seen in fig. 15.

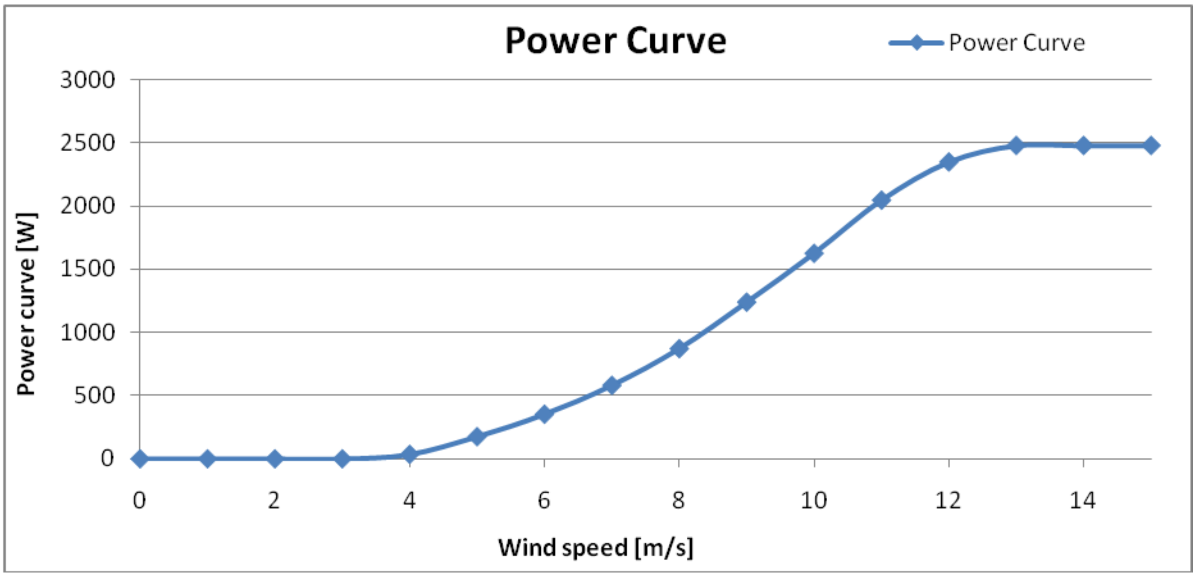


Fig.15. An example of how a power curve may look. It shows the output effect from a wind turbine.

4.3.7.1 Nacelle method

To determine wind speed between 5 % and 95% of rated power, the wind speed measured at the nacelle V_n and the corrected wind speed V_H at hug height which is determined from electrical power output is combined in a linear regression. For wind turbines with active power control V_H is corrected for the current air density which is determined from:

$$V_H = V_D \left(\frac{P_{ref} T_k}{p T_{ref}}\right)^{\frac{1}{3}} \tag{11}$$

Equation 11. Correction of the wind speed at hub for active power controlled turbines

Where

V_D	is the wind speed from the power output curve [m/s]
p_{ref}	is the reference air pressure 101.3 kPA
T_{ref}	is the reference temperature in Kelvin 288 K

The method to calculate the wind speed from the power curve is allowed to 95% of the maximum output effect of the wind turbine, a linear regression has to be used.

The wind speed at nacelle height has been scaled to the wind speed at 10 m height assuming logarithmic wind speed gradient. Equation 12 is from the standard [2].

$$V_S = V_Z \left(\frac{\ln\left(\frac{z_{ref}}{z_{oref}}\right) \ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H}{z_{oref}}\right) \ln\left(\frac{z}{z_0}\right)} \right) \tag{12}$$

Equation 12. Correction of the wind speed at nacelle height to 10 m height

Where

V_S	is the standardised wind speed [m/s]
V_Z	is the wind speed measured at anemometer height z [m/s]
z_{ref}	is the reference height of wind speed measurement 10 m
z_{0ref}	is the reference ground roughness length 0,05 m
z	is the anemometer height [m]
z_0	is the ground roughness length at the location [m]

4.3.7.2 K-factor method

Another method, which is not assuming a wind speed gradient, is the K-factor method.
It is used for an output effect less than 95% of the wind turbines max output effect.

$$V_S = \mathrm{K}\, V_Z \tag{13}$$

Equation 13. The equation for the K-factor method

V_Z in this method is the measured wind speed from the wind mast instead of the nacelle anemometer. The nacelle anemometer method is preferred because the correlation between the wind speed measured at the nacelle and the power curve effect output is better than for the wind speed measured with the wind mast. [2]
However, for background measurements when there is no power curve the wind mast is required.

4.3.7.3 Determination of wind speed with an anemometer

For the field study, a wind mast was utilized in combination with the wind speed calculated from the power curve. The wind speed was corrected to the reference height and reference roughness length as described in eq. 12. During the background noise measurements, when the wind turbine is parked the wind mast is appropriate for wind speed measurement. The allowable height of the anemometer is seen in fig. 16 which is taken from the standard [2].

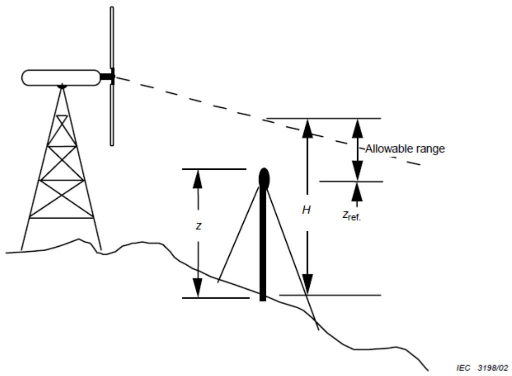


Fig.16. The allowable range for the height of the anemometer [2]

5 Analysis of field study

5.1 Outline of analysis

The results have been analyzed according to the conditions from the standard [2]. To determine the directivity, the background corrected noise level and the distance is needed. The background corrected noise level should be an equivalent sound pressure level over a period of 1 minute.
The sound pressure level was measured and stored every second in third octave bands, while the wind speed was stored every minute. Thus, the sound pressure levels were energy averaged into equivalent levels over 1 minute in MS Excel® to be matched with the wind speed at that period of time.
The values were corrected for the insertion loss of the primary wind screen in the sound level meter and for secondary wind screens in MS Excel® (the calibration factors and method can be seen in Appendix C). The sound pressure levels were A-weighted and then analyzed by frequency analysis, regression analysis, statistical analysis and tonal analysis. These values could then be used to determine the directivity. In this chapter the analysis needed to determine directivity and the corrections that were conducted will be presented first, then the directivity will be presented in 5.5.

5.2 Frequency analysis

A frequency analysis is performed to determine how the sound pressure level is affected by the wind speed and if there is strong sound sources that seems particular such as strong tones.
The analysis was performed in MS Excel® and presented in third octave band.
Due to the high wind speed during the measurement, there was disturbance from wind noise at the microphone which can be seen at the low frequency third octave bands.
It is difficult to extract the high frequency wind induced noise from the noise from the wind turbine when investigating sound pressure levels. Fig. 17 shows a frequency analysis of the reference point.

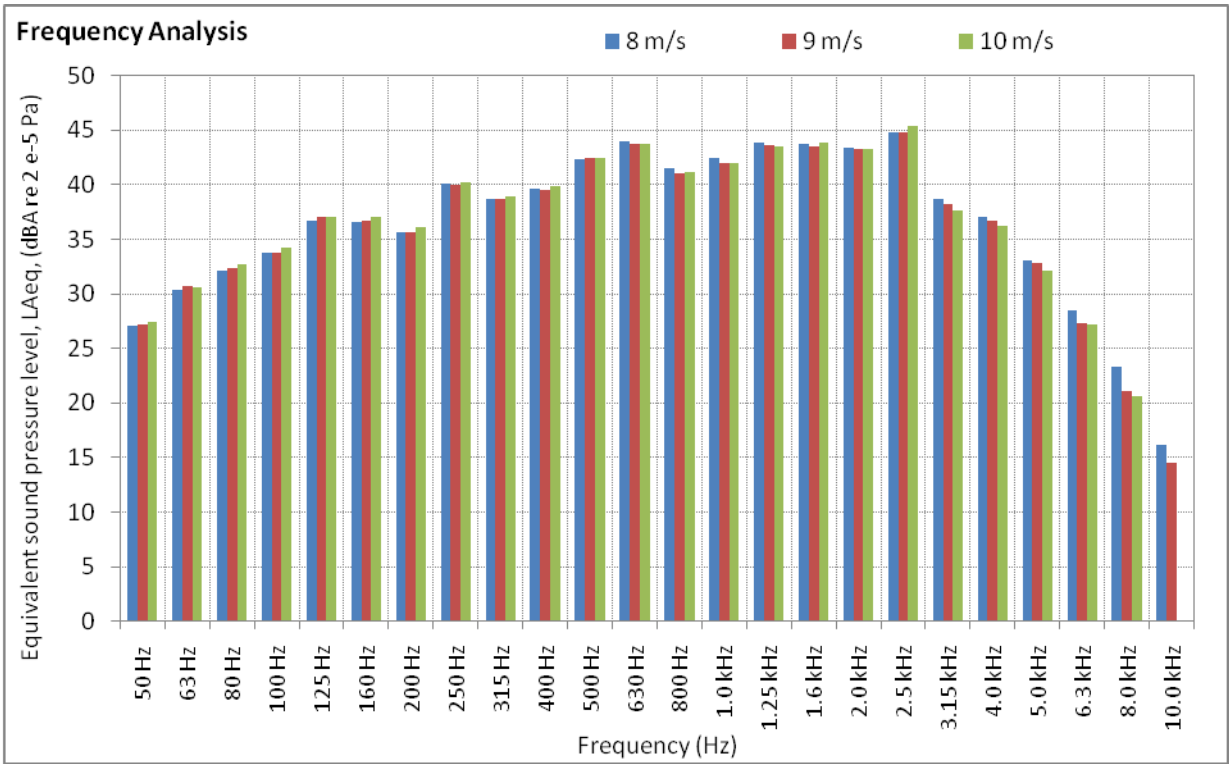


Fig.17. Frequency analysis in third octave band of the reference point

5.3 Statistic analysis

To determine if the results are normally distributed a statistical analysis is performed to determine if there are any abnormalities in the measurement.

A simple method to investigate this is to perform a graphical test for normal distribution.

This is performed by calculating the sound pressure level corresponding to a certain percentage of the overall sound level, this is presented as a line representing a threshold through a third octave band. This line is called for example LA90 which is the noise level exceeded for 90 % of the time considered. LA_{30} are the lower dotted lines and LA_{10} the upper dashed lines seen in fig.18 and fig. 19.

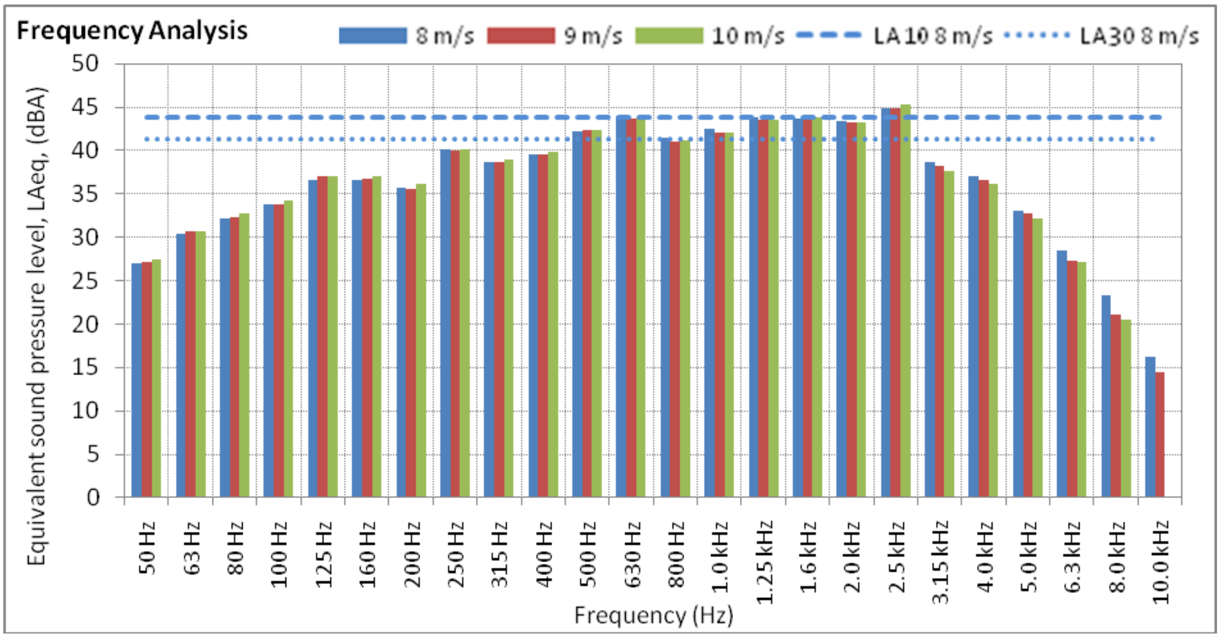


Fig. 18. LA_{30} and LA_{10} for third octave band levels at 8 m/s wind speed

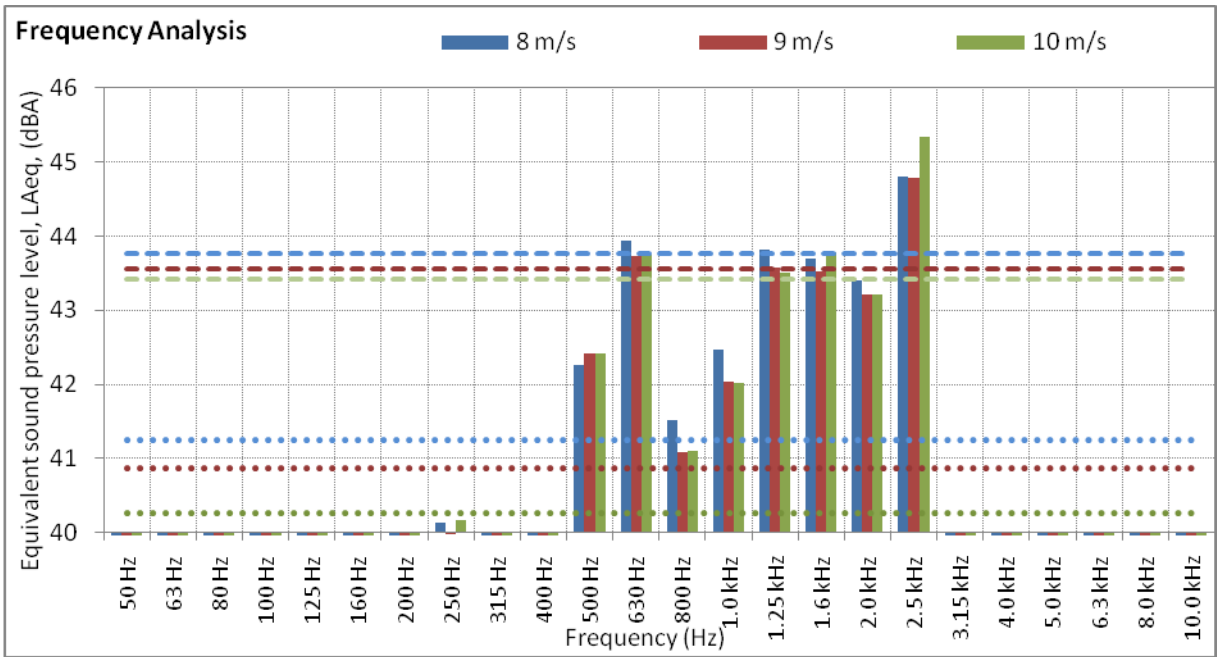


Fig. 19. LA_{30} and LA_{10} for third octave band levels at 8, 9 and 10 m/s wind speed (zoomed in on fig.18)

The spectrum analysis shows that there are tones at 125, 250, 630 and 2.5 kHz.

The tones at 125, 250 and 2.5 kHz origins from mechanical noise, 630 Hz may be gearbox-noise.

5.4 Regression analysis

5.4.1 Summary of the regression analysis

According IEC 61400-11 [2] wind turbine noise is determined using the equivalent A-weighted sound pressure level. To analyze the data a 4th order regression analysis should be applied to get the apparent sound pressure level. A similar regression analysis should also be made for the background noise. If the correlation is greater than 0.8 the 4th order analysis should be used, if it is less a linear regression should be made dependent of the wind speed and divided into integer bins from it.

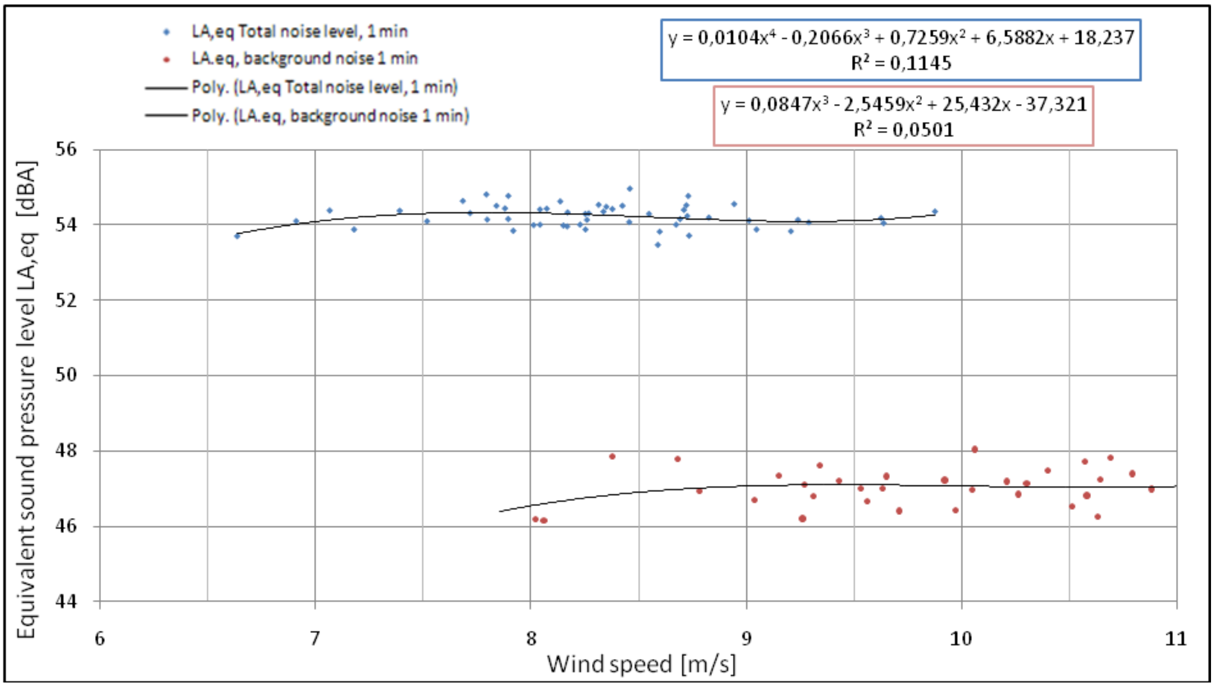


Fig. 20. Regression analysis of sound pressure level at reference measurement point

Fig.20 shows the regression analysis of the measurement point positioned crosswind in the reference point. The characteristics of the regression curve shows that the sound pressure level peaks at 7,5 m/s and at higher wind speeds the noise level decreases until it reaches 9,5 m/s where it increases once more. Similar characteristics could be observed at all measurement points and the regression curves can be seen in Appendix A. The background noise increases with increasing wind speed.
Due to the low coefficient of determination (R^2=0.1145), a bin analysis were performed for each integer value of the wind speed between 6 and 10 m/s, which is according to standard.
This is performed by separating the total noise and backgrounds noise to wind speed bins for 6, 7, 8, 9 and 10 m/s and analyzing with linear regression.

Wind Speed [m/s]	6	7	8	9	10
Lp_A, eq,1min [dBA]	52,8	54,1	54,3	54,1	54,5
Lbg [dBA]	41,9	45,0	47,1	47,1	47,1
Delta	10,8	9,1	7,2	7,0	7,4
Ls [dBA]	52,4	53,5	53,4	53,1	53,6
$Lw_{,A}$ [dBA]	100,8	101,9	101,9	101,6	102,0

Table 6. Bin analysis of integer value of the wind speeds for the data from the reference point

Where

Lp_A eq	is the equivalent sound pressure level energy averaged over 1 minute.
Lbg	is the background noise, the sound pressure level energy averaged over 1 minute
Delta	is the difference between total noise level and background noise level.
Ls	is the background corrected noise level
Lw_A	is the sound power level

The bin analysis shows similar results as the regression curve for the reference point. However, for other measurement points a 4th order regression did not give a satisfying approximation for sound pressure levels at wind speeds between 6-7 m/s.
Thus a bin analysis with linear regression for each wind speed was done for each measurement point and the data for the presentation of directivity is based upon that analysis.

The sound power level for a wind speed of 8 m/s at 10 m height:
Bin analysis with linear regression: 101,9 dBA.
Regression analysis of 4th order**:** 101,9 dBA
The 4th order regression analysis with corresponding sound power level is seen in figure 21.

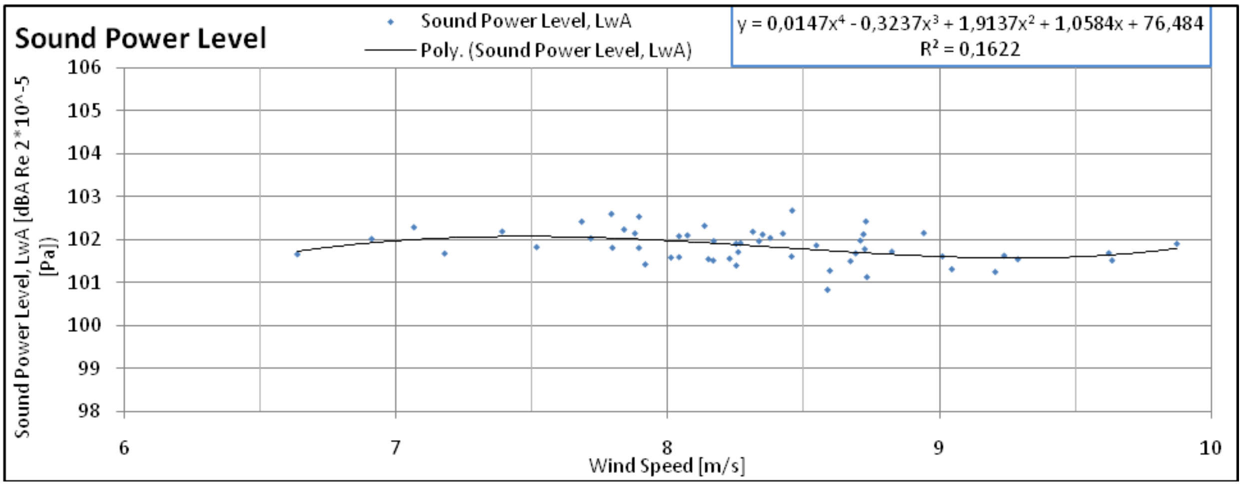


Fig. 21. Regression analysis of sound power level at reference measurement point

5.4.2 Corrections conducted in the regression analysis

The sound level meters at position M1, M2 and M6 (see fig.13) recorded sound for the possibility to locate abnormal sounds such as vehicles or animals.
By listening to the different recordings a constant bird tweet was detected, the birds were close to measurement positions M2 and M6 and by comparing the background noise recordings when the birds were active and inactive it could be concluded that the third octave bands 5.3 kHz and 6.0 kHz were affected by the tweet. An average of the all the measured sound levels between the affected measurement points M2, M6 and M5 relative to M1 was performed and a correction were made for all sound levels in the affected third octave bands.

M2 in relative to M1	3.15 kHz	4.0 kHz	5.0 kHz	6.3 kHz
Average difference	0.82	1.68	3.33	2.56

Table 7. Example of the average difference in third octave band levels between M2 and M1

5.5 Directivity of the sound

5.5.1 Description of the analysis of directivity

The sound pressure levels corrected for background noise retrieved from the bin analysis have been adjusted by the difference in distance for each measurement point according to equation 3.
The comparison between the corrected values then constitutes a pattern for the horizontal directivity of the total noise emitted from the wind turbine.

The directivity will be presented either as a polar plot with a circle representing the line on which the measurement points have been placed around the wind turbine seen in Fig. 6a.
The circle will also be presented along a straight axis as in fig.22 with two 'dips' corresponding to the crosswind direction or as a directivity index, which is the sound pressure levels in the measurement points relative to the sound pressure level in the reference point Fig. 23.

For the sake of presentation, some data from points have been used on the opposite side of the wind turbine to interpret the whole sound radiation pattern. This would be true if symmetry around the wind turbine could be assumed. This is not the case, the true sound radiation pattern is only at the measurement points, and the lines between two measurement points are only interpolation. (M1=0°, M5=30°, M2=60°, M6=90°, M3=180°, M1=300°)
An example of a 'mirrored' measurement point is M6=90° which also is used as M6=270°

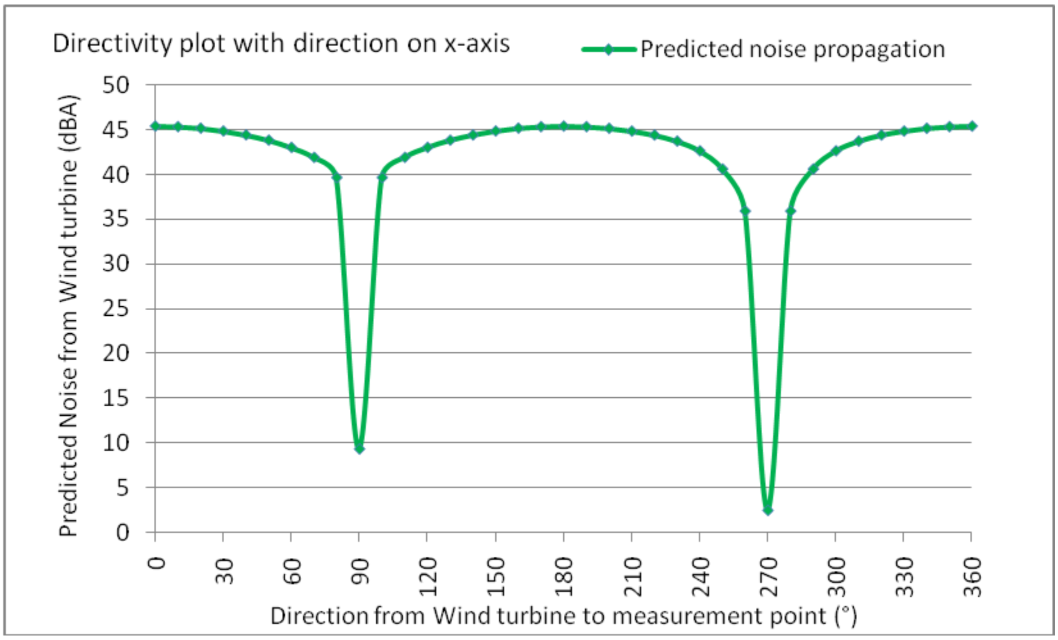


Fig. 22. Wind turbine noise prediction of the horizontal plane presented as a point diagram

In figure 22 a wind turbine noise prediction code from [5] has been used, it is apparent that there is a 5 dB difference between the two dips. The reason is shown in fig.1 where an acoustic camera shows how the sound radiated towards the ground is louder when the rotor is revolving downwards in comparison as to when it is revolving upwards.
This has not been implemented in the simulation used in this report. However, as the data used at 270° is the same data as for the measurement point at 90° it is redundant.

5.5.2 Directivity Index

According to the standard [2] a method of showing the directivity of a sound source is the directivity index. In fig.23 the directivity is shown according to equation 3 in chapter *2.1.4 Directivity of sound.* The curves are based on the sound pressure levels corrected for background noise for all the measurement points. For a orientation on where the measurement positions are see fig.13. Additionally an assumption of the sound pressure level at 270° being the same as at 90° have been made. This is not essentially true because symmetry cannot be assumed. However, it gives a better insight of the overall directivity around the wind turbine as mentioned in 5.5.1.

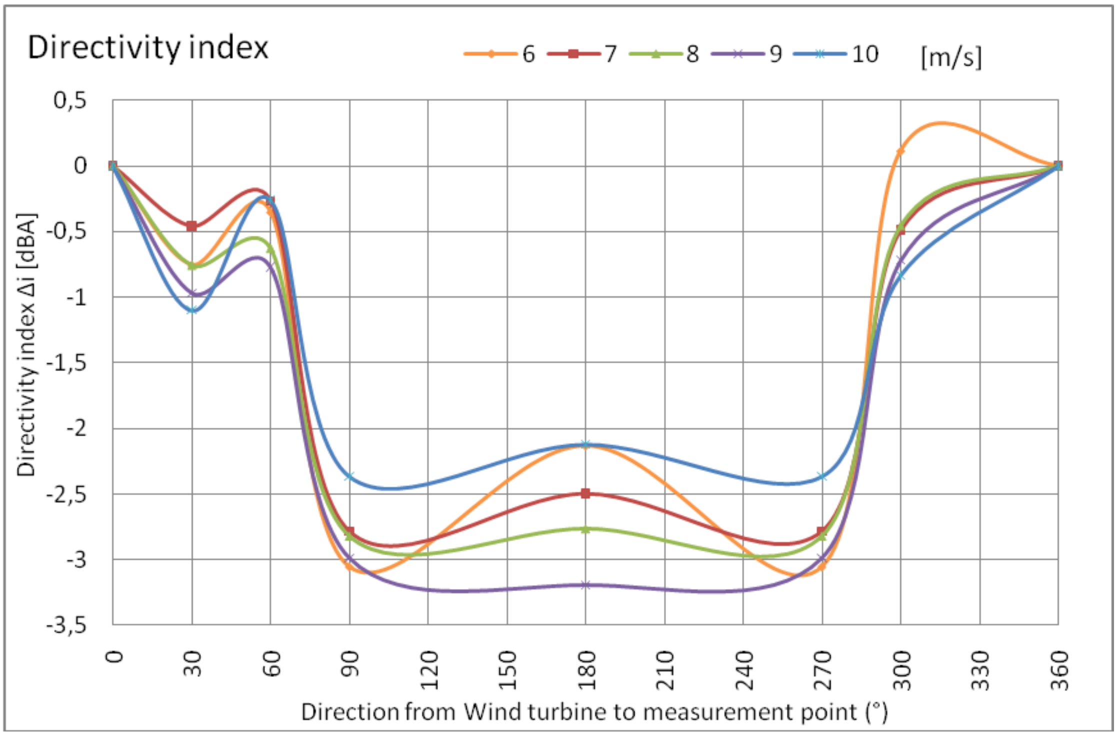


Fig. 23. The sound pressure level around the wind turbine relative to the reference point

In figure 23 the directivity in the far field for a wind turbine is shown. It shows how the sound pressure level is different depending on the position of the observer and the wind speed.
The angle 0° corresponds to the position downwind of the wind turbine which is reference point M1
The angle 90° corresponds to the position in crosswind of the wind turbine, perpendicular to the wind direction (M6)
The angle 180° corresponds to the position which is upwind of the wind turbine (M3).
The measurement points at 30° (M5), 60° (M2) and 300° (M4) is also included in fig.24
Notice that the curves are over determined due to interpolation for example at 301°-360° for 6 m/s

		Wind Speed [m/s]				
		6	7	8	9	10
Directivity Index	Δ2	-0,35	-0,26	-0,63	-0,77	-0,26
[dBA]	Δ3	-2,13	-2,50	-2,77	-3,20	-2,12
(Rel. $2*10^{-5}$ Pa)	Δ4	0,12	-0,49	-0,46	-0,72	-0,83
	Δ5	-0,75	-0,46	-0,76	-0,97	-1,1
	Δ6	-3,05	-2,78	-2,82	-2,99	-2,37

Table 8. The directivity index for all measurement points relative to the reference point.

5.5.3 Directivity at frequency range of aerodynamic sound sources

It is determined that the aerodynamic sound sources from the blades are the dominating source of sound from modern wind turbines [19]. The directivity investigated in the simulation is aerodynamic sources which gives reason to investigate the frequency range where aerodynamic sound is apparent. This is conducted by summing the A-weighted sound pressure levels between 250 and 800 Hz which is the frequency range dominated by turbulent boundary layer noise.
There is a tendency for the measured values similar to the predicted but the difference in magnitude in the crosswind position between the measured and predicted values is distinct.
In figure 7, where the predicted values are modified in the crosswind position to match a realistic case the magnitude at 90° and 270° is –6 dB relative to the reference point. According to the simulation used in this study, it is -14 dB relative to the reference point. In reality, according to the field study it is -3.5 dB relative to the reference point. The measured values are plotted as a function of the direction of the wind turbine and have been averaged when the angle is the same, thus the spread of the clusters seen in figure 24. In Figure 25 the directivity index is shown.

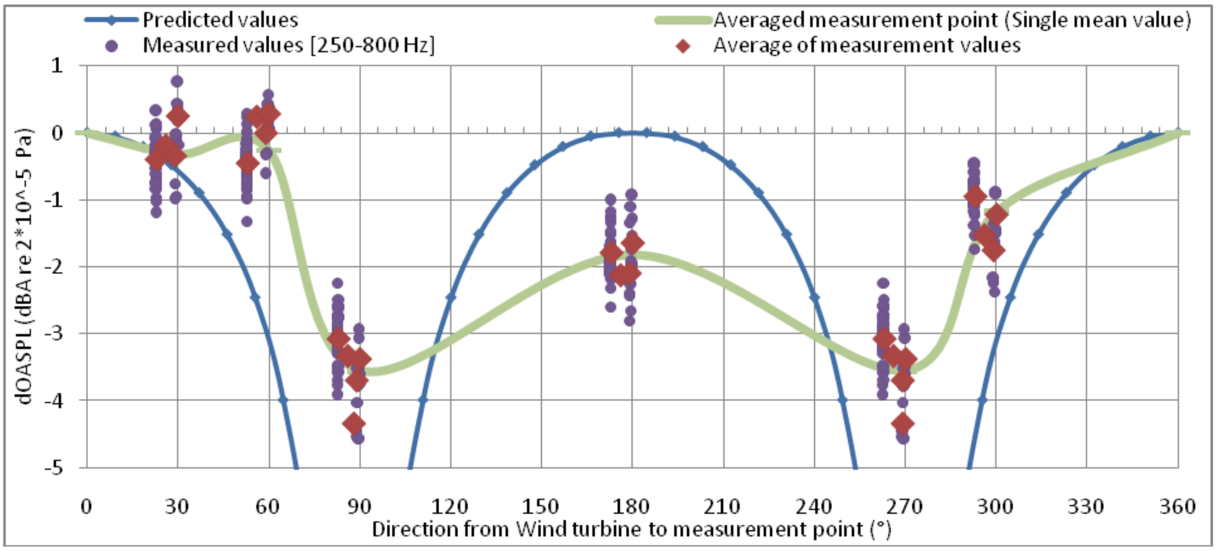


Fig. 24. A comparison between measured and simulated sound level around the wind turbine

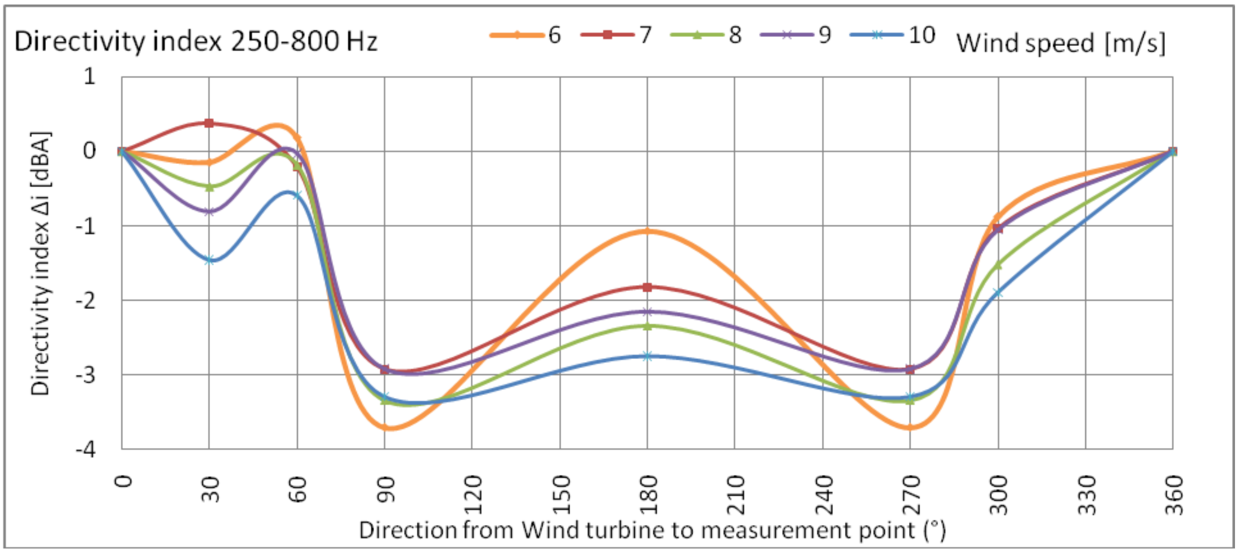


Fig. 25. A comparison between measured values at different wind speeds between 250-800 Hz

5.5.4 Directivity shown as polar plot

This chapter contains polar plots of the directivity with a comparison between prediction and measurement. It is seen in figure 26 that the measure sound levels between 250 and 800 Hz, where blade tip noise at 1 kHz is excluded, which is the frequency range of the trailing edge noise does not follow the predicted sound levels of trailing edge noise. There is a decrease in the measured values but due to background noise and other sources in the same frequency range the attenuation is not close to the predicted. The sound pressure level as a function of nacelle direction seen in fig. 24 is used as a polar plot in fig. 27. For orientation see Fig.13 in chapter 4.3.1.

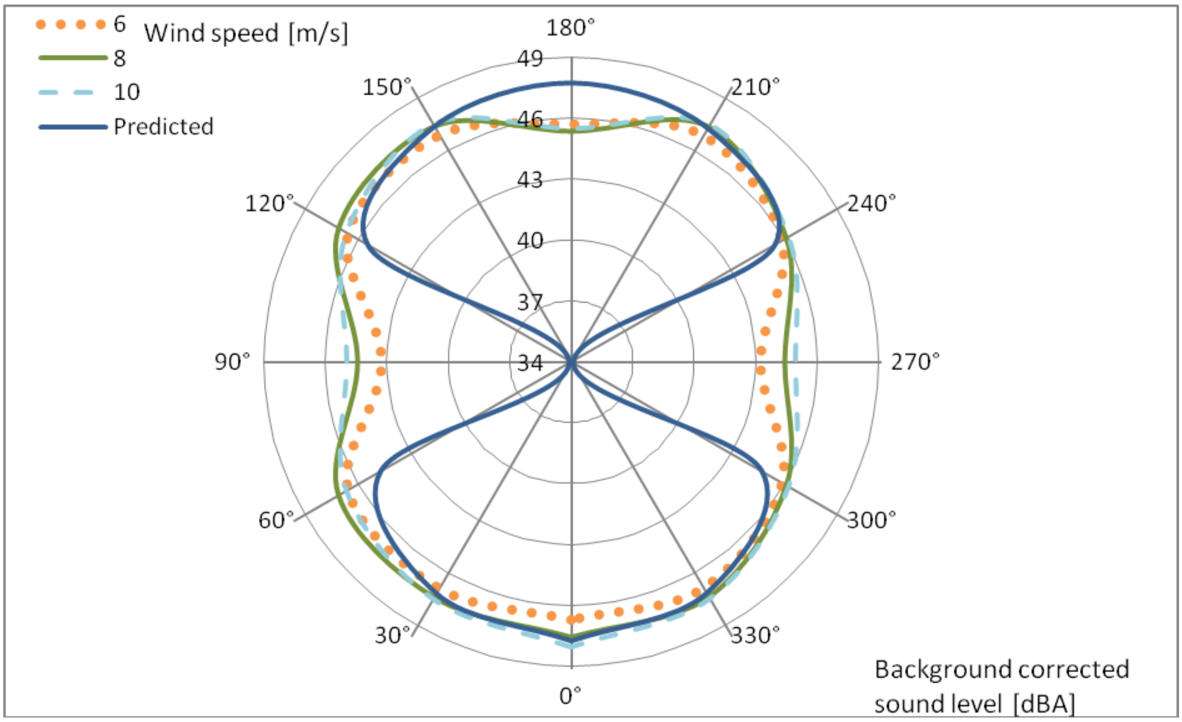


Fig. 26. Directivity shown as a polar plot for sound pressure levels between 250 and 800 Hz

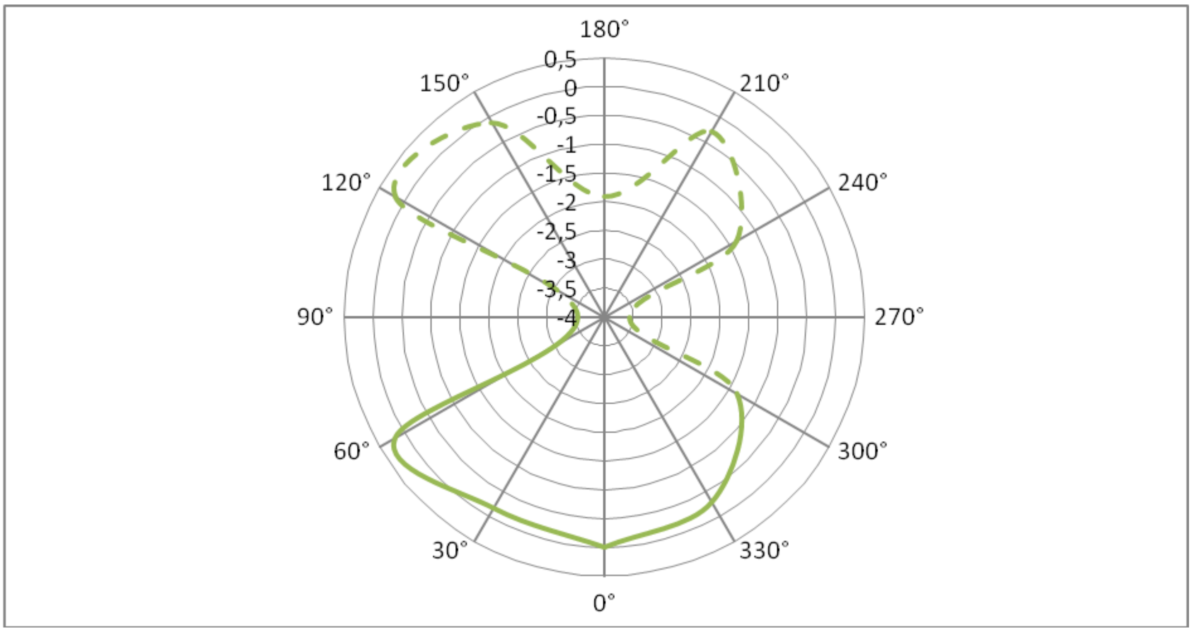


Fig. 27. Directivity shown with point 240° interpolated from point 300° and same values as in fig.24

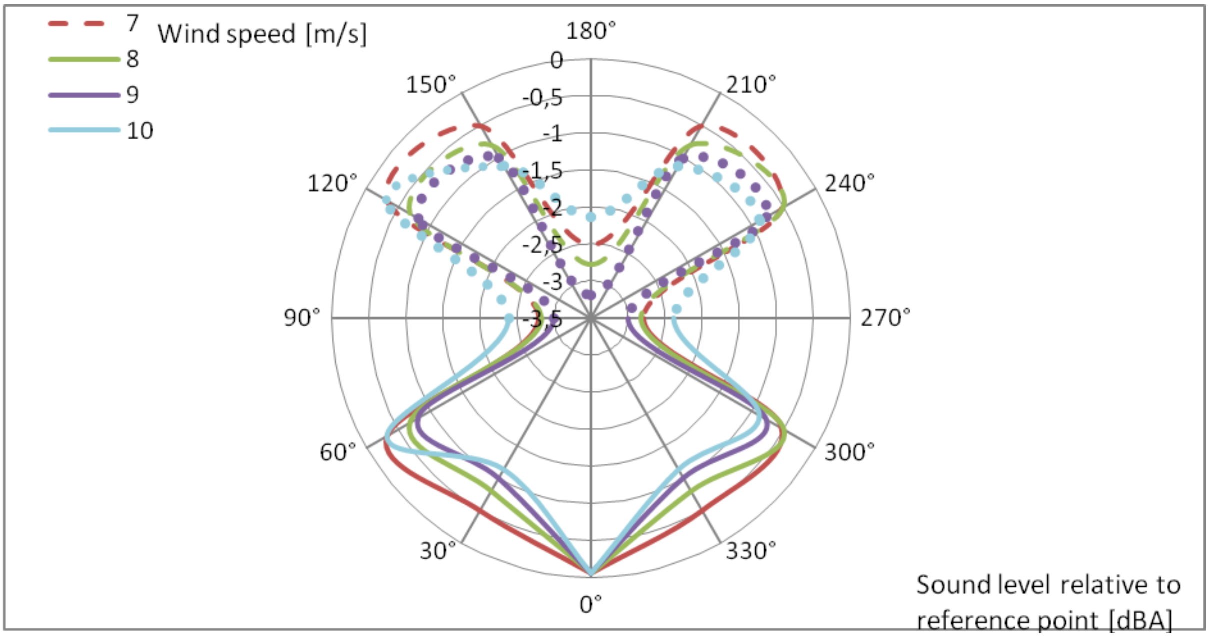


Fig. 28. Directivity shown as a polar plot sound pressure levels relative to reference point

In figure 28 the sound pressure level corrected for background noise is shown for the frequency range 20 – 20000 Hz. The upwind measurement point has relatively low sound pressure levels and thus a symmetric view of the measurement points does not show a representative picture of the directivity. The upwind sound pressure levels are shown in dashed lines as it is unknown except for the measurement point at 180°. Even though the plot in figure 26 only shows the sound levels in the frequency range 250-800 Hz, similar results is seen for the whole frequency range as the attenuation in the crosswind direction is around 3 to 4 dBA relative to the reference point. However in the upwind direction the sound pressure levels are relatively high in comparison to the sound levels for the measured frequency range 20-20000 Hz.

5.5 Uncertainty

The uncertainty of the measurements have been evaluated according to standard [2] for each regression analysis. The method that have been implemented is shown in appendix B which explains what factors are considered for the uncertainty and an example of values from the measurement in reference position. The combined standard uncertainty is the individual standard measurement uncertainties associated with the input quantities and have to be considered when evaluating the results. The combined uncertainty for the regression analysis conducted for the reference point is ±0,78 dBA. The value depends on site condition and is an acceptable value according to the author.

5.6 Method evaluation

In the field study, all sound sources are included while in the prediction, only trailing edge noise is accounted for. For a correct comparison, an integration contour that would separate the trailing edge noise from other noises would be preferred instead of summing the A-weighted sound levels between 250-800 Hz together. The reduction of the third octave band levels due to bird noise may be incorrect and a band-stop filter would have been preferred. Symmetry around the wind turbine cannot be assumed, the duplicated measurement points around the wind turbine may give an incorrect view of the directivity pattern. More measurement points to achieve higher resolution are recommended to determine directivity. However, the method is sufficient according to the author.

6 Discussion

6.1 Concept of the study

The aim of this study was to investigate how the directivity of the sound sources from a wind turbine influenced the sound radiation and how this could be applied to optimize the power output while still fulfilling the conditions of noise at nearby building from different guidelines.
The turbulent boundary layer trailing edge noise was the sound source that was mainly focused on in this study due to it being the dominant sound source on modern wind turbines and because the aerodynamic sound is more likely to have a strong directivity compared to mechanical noise.
The method used to investigate the directivity was based on a literature study and a following field study. From the literature study it is apparent that the international standard [2] which includes a method to investigate directivity from wind turbines has been tested with modifications in several studies. Furthermore, several wind turbine noise predictions have been created based on the simulation from *Airfoil self noise and prediction* [18]. Both field studies and simulations of the directivity from different reports come to the same conclusion mentioned in 7.2.

6.2 Results of the literature study

There is a decrease of sound level in the crosswind direction of the wind turbine due to the dipole character of the aerodynamic noise, especially due to the directivity of the trailing edge noise which is the dominant sound source. Furthermore, due to refraction more than the directivity of the source there tends to be lower sound levels upwind of the wind turbine in areas of 'sound shadow'.

6.3 Results of the field study

The method used for the field study included emission measurements according to the setup for directivity measurement from the standard [2] with a modification of adding two measurement points to increase resolution in a quarter of a circle. The measurement positions covered important directions from the wind turbine, however when investigating the full sound radiation pattern the resolution was relatively low and a separation of 15° between each measurement point would have been preferred. The results from the field study did not comply with the predicted sound pressure levels. This was due to the fact that the prediction code only covered the dominant aerodynamic sound source, the trailing edge noise. The trailing edge noise which has a dipole characteristic of directivity and thus decreased rapidly in the crosswind direction due to the directivity function for trailing edge noise (eq. 5) could not be directly compared to a measurement of the total noise as other sources, both from the wind turbine and background noises becomes dominant in the area where the trailing edge noise is decreased.
From the field study it is shown that the sound pressure level corrected for background noise in the crosswind direction is approximately 3-4 dBA less than the sound pressure level corrected for background noise at the reference point. According to prediction, it should be approximately 15 dB less. This is not realistic however. To compare the prediction with measured values an integration contour to separate the trailing edge noise from the measured values would have been required.
The relatively low sound pressure level in the upwind direction is most likely due to refraction.
It would have been optimal to measure wind speed at ground at each measurement point, however it was measured according to standard with a wind mast upwind of the wind turbine.
Due to high wind speeds it is questionable if the wind screens managed to protect the microphone.
The total noise level over the whole frequency range is however directional from the wind turbine, but the difference in sound pressure levels around the wind turbine are considered small.

6.4 Reflections about the analysis

The concept of the analysis was to analyze each measurement point according to standard [2].
This was conducted by relating the sound pressure levels of the total noise when the wind turbine was active to the wind speed at the moment of recording and then correcting the sound pressure levels of the total noise by the background noise at the related wind speeds.
To achieve the correct values at certain wind speeds, a 4th order regression analysis for each measurement point were performed, and if the coefficient of determination was relatively low (less than 0.8 according to standard [2]) a bin analysis with linear regression for each value integer of the wind speed was performed instead. This is the standardised method for emission measurements of wind turbines conducted at present day and is an established method for sound level measurements of wind turbines in Europe. The presentation of directivity according to the standard [2] is the directivity index. The other methods of presenting directivity, such as assuming symmetry to give a better view of the whole pattern around the wind turbine, are created by the author and should be considered critically. For example, it is claimed that practically all downward radiated blade noise is produced on the blades downward movement [10, 19] still an assumption of symmetry in the crosswind direction have been made to give perspective of the directivity around the wind turbine.
The correction for bird tweet is a quick solution to a complex problem and should be considered critically. Directivity is frequency dependent and should be investigated more thoroughly.
The wind speed was higher during the background measurement compared to the total noise measurement, this causes the shift between the total noise data points and background data points in the regression analysis and for lower wind speeds (6-7 m/s) the regression trend have to be trusted. However, this increases the uncertainty as it is an assumption of the characteristic of wider span of wind speed than was actually measured.

6.5 Query method

The query method used for the literature study was focused on directivity of sound from wind turbines and the databases used are from the database collection at the library of the Royal institute of technology. The reports used in the literature study and the information from them used in this paper are considered reliable according to the author of the present paper.

6.6 Influence of the uncertainty

The measurement period were one hour with the wind turbine active and half an hour with the wind turbine parked. The period satisfactory according to standard, however it only covers a limited range of wind speeds. Thus it is uncertain how representative the background noise and total noise actually are for regular noise levels at those wind speeds. This could perhaps be doubtful because the results from the analysis are restricted to daytime.
The direction of the wind turbine was evaluated to be in the range of an angle ±15° relative to the reference point, this was however uncertain and was measured by the eye. The other measurement points were related to the reference point with distance meter.

There are several factors of uncertainty which have been approximated and the combined factors have to be considered when evaluating the results. These factors are for example the standard error of equivalent sound pressure levels, calibration, instrumentation such as ground board, instrument chain, distance measurements, acoustic attenuation of air, meteorological variations, wind speed, wind direction and background. The calculation of the uncertainty can be seen in Appendix B.

6.6 Sources of error

Apart from the sources of error mentioned in the influence of the uncertainty it should be noted that the method for correction of bird noise is a matter of concern. The soil under the ground board was flattened out to avoid acoustic resonators due to cavities between ground and board, this was conducted quickly and small cavities may have influenced the measurement. The influence of the secondary wind screens at the relatively high wind speed at ground due to the flat land of the region is uncertain and the limit of the protection against wind induced noise at the microphone is not known. However, the wind screens were made according to standard and similar wind screens are approved fully in [15]. The results seem overall relatively reliable compared to what was expected before the field study according to the author.

7 Conclusion

This study have been conducted to investigate the directivity of sound from wind turbines in order to determined if it can be used to optimize the wind turbines output effect while still fulfilling the guidelines of the sound pressure levels outside of nearby buildings.
In this study that is presented in this report the conclusions that could be made were:

- There is an apparent directivity for the total noise of a wind turbine where there is lower sound levels in the crosswind direction compared to other points around the wind turbine with equal distance from the source.
- The horizontal directivity pattern is of a dipole character due to the fact that the emitted sound from the dominant sound source is decreased in the crosswind direction.
  The aerodynamic sources which are also of a dipole character along the blade's foil in the vertical plane constitute the directivity in the vertical plane as well as the horizontal.
- The decrease of noise in the crosswind direction is not as prominent as suggested by the theoretical prediction of the dominant sound source, due to the fact that other sound sources contribute to the emitted sound in the crosswind direction and that the background noise influences the measurement in the field study.
  For a correct comparison an integration contour of the aerodynamic sound source is required to separate the dominant sound source from the total noise at the location of the field study.
- The knowledge of the decrease of total noise in the crosswind direction could be used to optimize the output effect of the wind turbine. If the wind turbine is limited due to the sound it emits it could be regulated with the pitch angle of the blade when the crosswind direction is facing nearby buildings to optimize the output effect. The difference in total noise is relatively small and one have to consider the fact that the sound emitted may be louder at lower wind speeds than the wind speed where the wind turbine has optimized output effect.

There is a horizontal directivity that can be observed from the measurements conducted in the field study. For the total noise, the sound pressure level measured at the point in the crosswind direction is 2-3 dBA less than the sound pressure level in the reference point depending on wind speed.
For the frequency range of the trailing edge noise the difference is 3-4 dBA varying on wind speed. Combined with the other measurement points, the dipole character of the horizontal directivity is shown and by comparing the measurement to the noise prediction the dipole character trend is not verified but it appears that with modification the prediction could demonstrate the directivity. The difference of sound levels is relatively low. The application of directivity to optimize output effect could be utilized, but the advantage has to be quantified before a conclusion can be made.

8 Future work

Decreasing noise from wind turbines

The newly built wind turbines are getting larger in both hub height and rotor diameter, due to this the problem of aerodynamic noise from the wind turbines will only increase if the blade design is not adjusted to decrease the noise. Thus the directivity of the aerodynamic sound might become more important in the future.
The blades are designed aerodynamically to optimize the output effect. However, some research has been conducted to investigate the character of the aerodynamic sound sources for jagged edges on the suction side of the blade. Such design may be of interest to decrease the trailing edge noise even though the aerodynamic properties of the blade may be decreased at the cost.

Modern wind turbines can be regulated to reduce the aerodynamic sound, this is done by adjusting the pitch angle of the blades. Another option is to reduce the number of revolutions or limit the time when the wind turbine is active. These options may be required at evenings and nights when the background noise is lower and nearby residents may be disturbed by the wind turbine noise.
Other solutions, such as a quieter design of the blades or regulation of the wind turbine adjustment due to the sound radiation pattern may be preferred to sustain the wind turbine active as much as possible. By a more thorough study of the predicted and measured directivity of a wind turbine a standardised system to regulate the noise from wind turbines could be utilized to both optimize the power output and preserve a low noise level. These are both important factors for the expansion of wind energy in the energy market.

Improvements of the field study

A field study with a denser measurement point setup around the wind turbine to increase the resolution of the directivity pattern together with imission measurement at a nearby building should be performed to estimate if the wind turbine could be optimized in output effect due to directivity. To decrease the uncertainty, the measurement should be conducted during a longer period, covering more wind speeds and also a longer period during the night to investigate how the noise varies dependent on temperature inversion.
This study is limited to the horizontal directivity. A field study of vertical directivity is a complex measurement where either measurement points at hub height or several measurement points on a row with different distance from the wind turbine is required. Assuming that horizontal directivity is the complete sound radiation pattern of a wind turbine is a simplification as the sound may propagate different at an altitude of hub height than it does at ground. Horizontal directivity considers observers on a close distance. It is however possible that the sound propagates further on a higher altitude and that the directivity pattern on longer distance is different.

Improvements of the wind turbine noise prediction

A more specific wind turbine noise prediction should be created. It should include the exact dimensions of the segments of the blade that are considered and the sound sources are associated with the segment where the source actually origin. A more accurate function that supersedes the extreme decrease of sound pressure level in the crosswind direction is required such as the prediction by Moriarty [20] or Oerlemans [19]. Furthermore, all sound sources from the wind turbine should be included if it should be compared to the total noise of a wind turbine.

9 References

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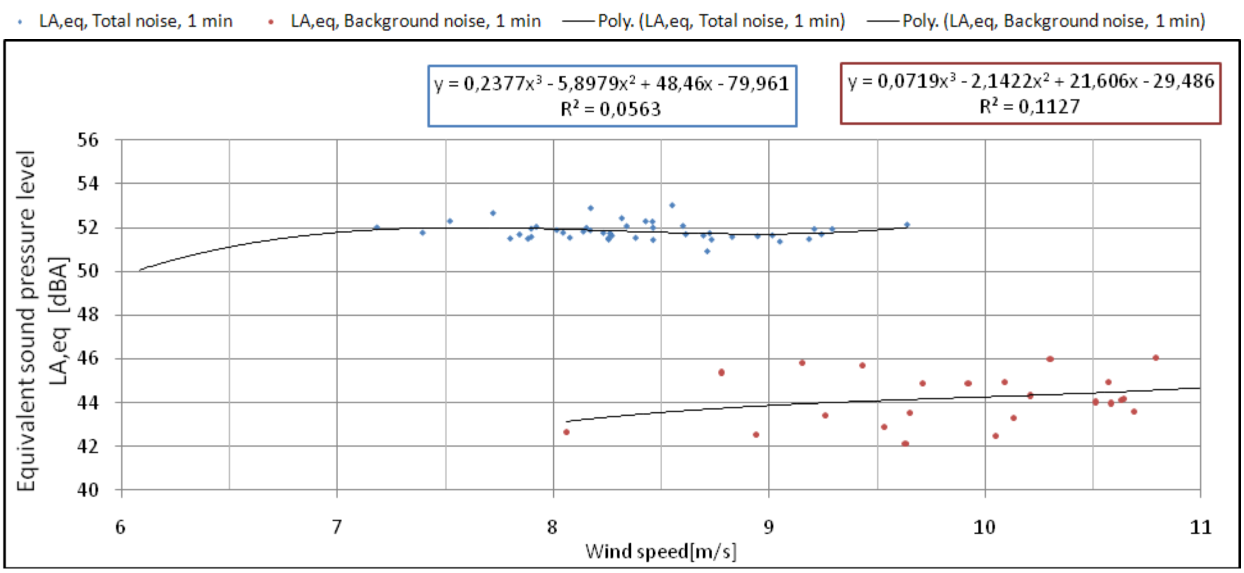
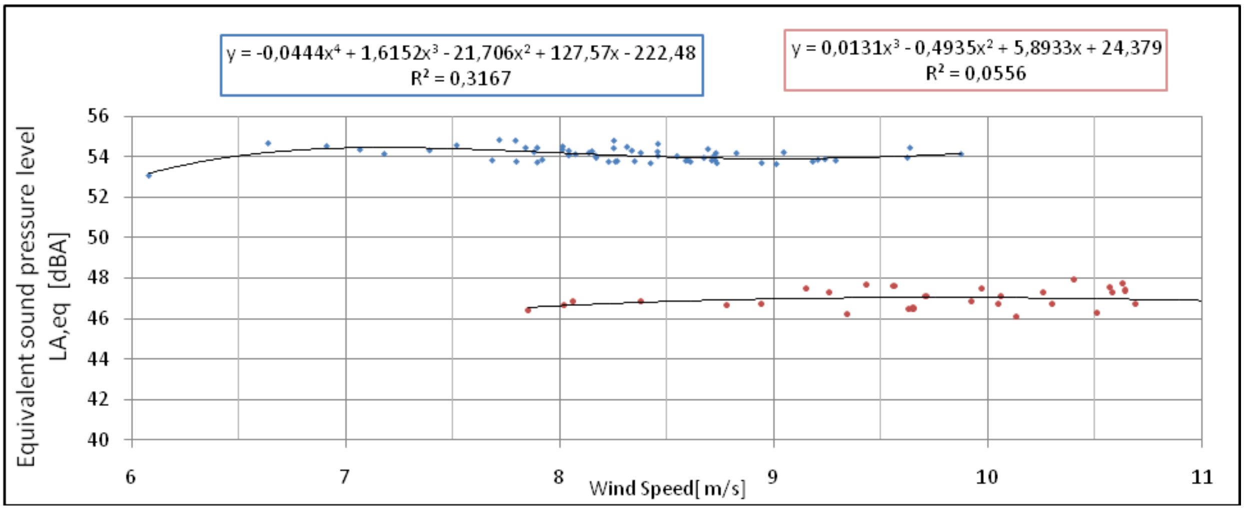
Appendix A Regression analysis and Bin analysis

AL161 M3



AL164 M5



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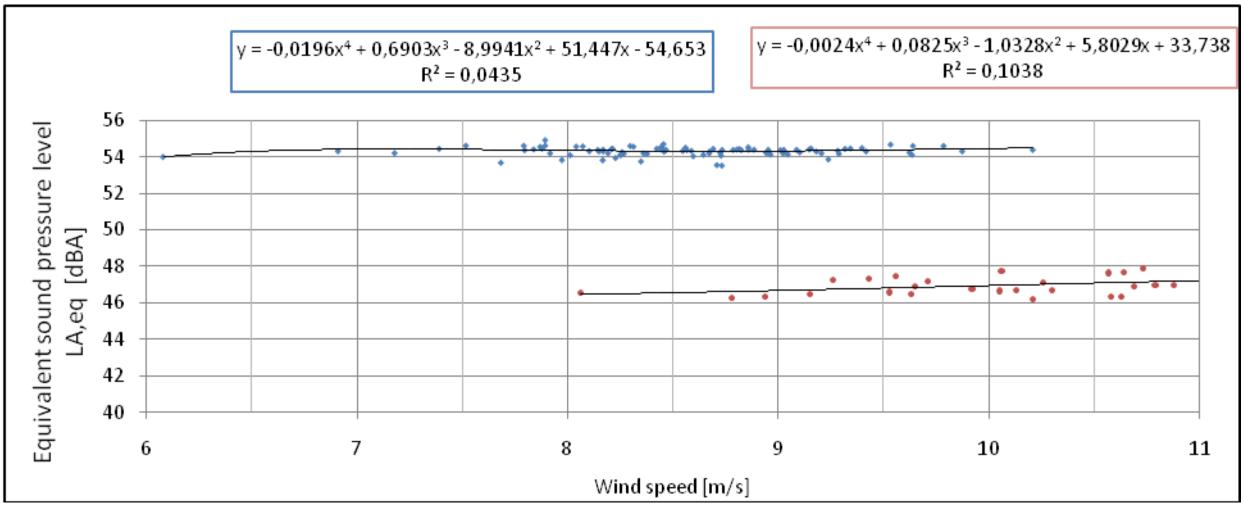
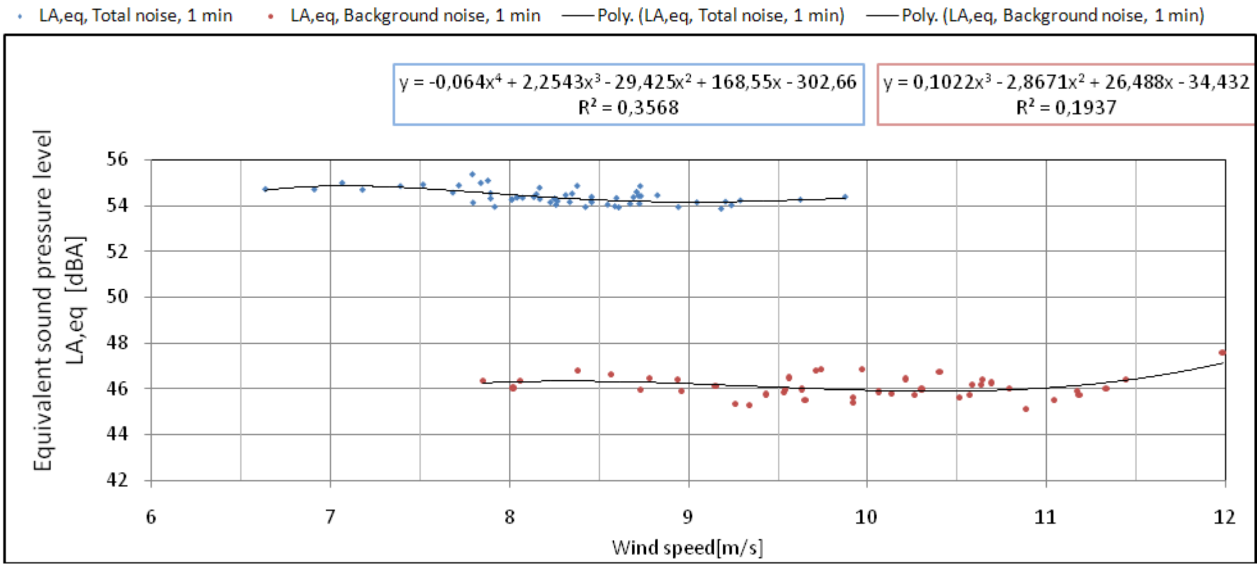
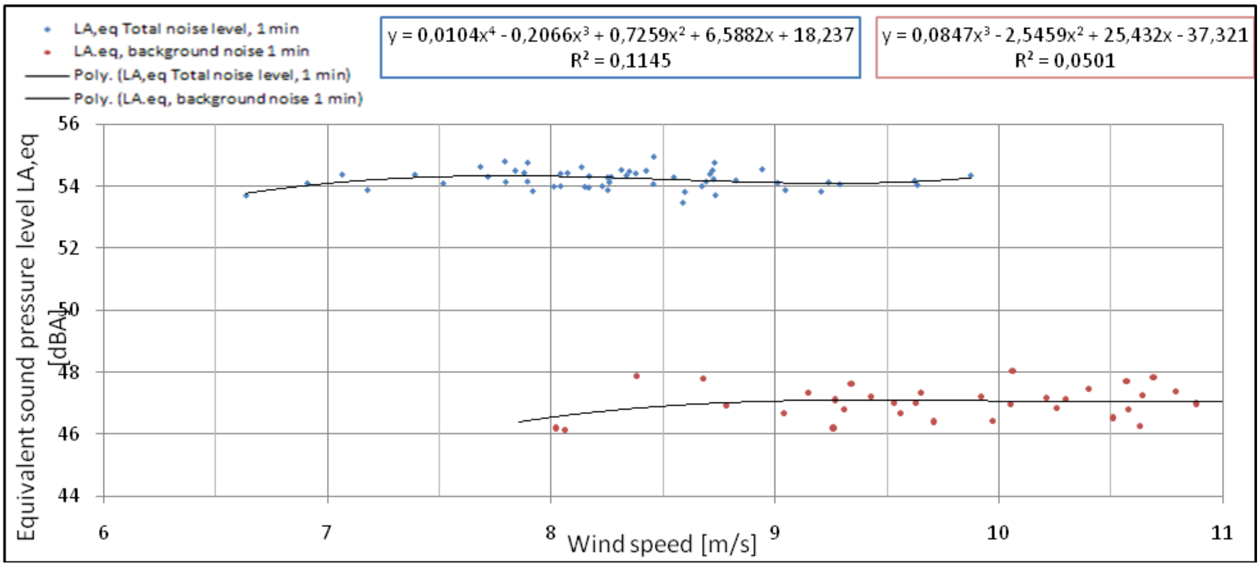


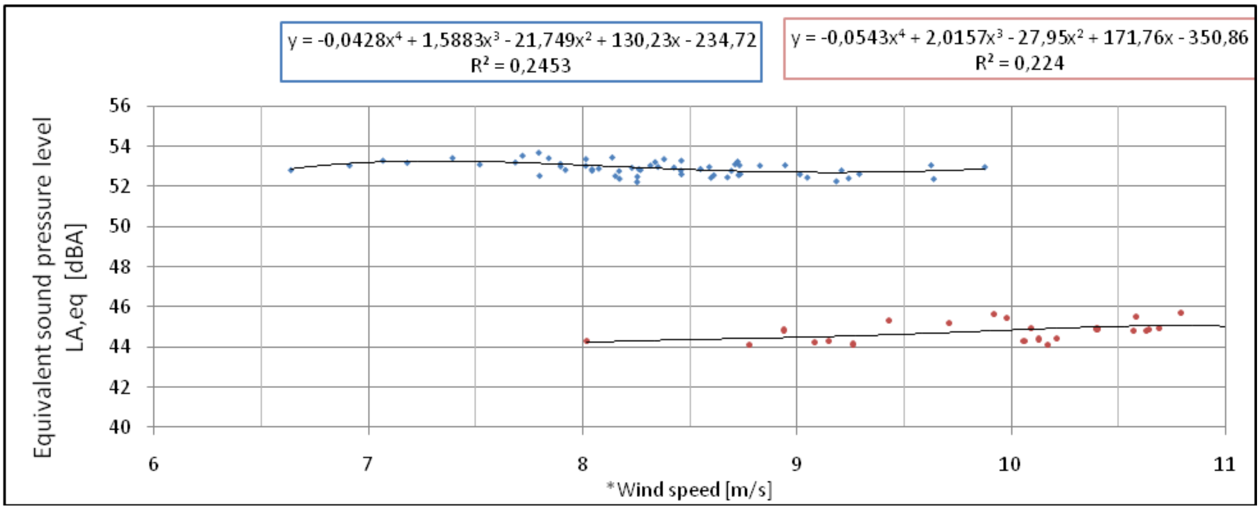
Al172 M2



AL196 M1



AL197 M6



				Bin Analysis					Regression 4th order		
	Wind Speed [m/s]	**6**	**7**	**8**	**9**	**10**	**6**	**7**	**8**	**9**	**10**
	Lp_A,eq,1min [dBA]	52,75	54,06	54,31	54,11	54,47	52,75	54,03	54,22	53,95	54,11
	Lbg [dBA]	41,91	45,01	47,07	47,14	47,10	41,91	45,01	46,56	47,10	47,11
M1	**Delta**	10,84	9,05	7,24	6,97	7,37	10,84	9,02	7,66	6,86	7,00
	Ls [dBA]	52,38	53,48	53,40	53,14	53,59	52,38	53,45	53,40	52,95	53,14
	Lw_A [dBA]	100,83	101,94	101,85	101,60	102,04	100,83	101,91	101,86	101,40	101,60
	Wind Speed [m/s]	**6**	**7**	**8**	**9**	**10**	**6**	**7**	**8**	**9**	**10**
	Lp_A,eq,1min [dBA]	53,48	54,78	54,49	54,16	54,97	55,48	55,50	55,03	54,72	54,98
	Lbg [dBA]	43,36	45,55	46,31	46,27	46,28	46,45	46,75	46,81	46,65	46,54
M2	**Delta**	10,13	9,23	8,19	7,89	8,70	9,03	8,74	8,22	8,07	8,44
	Ls [dBA]	53,04	54,23	53,78	53,38	54,34	54,90	54,87	54,32	53,99	54,31
	Lw_A [dBA]	100,48	101,67	101,22	100,83	101,78	102,34	102,32	101,76	101,43	101,75
	Wind Speed [m/s]	**6**	**7**	**8**	**9**	**10**	**6**	**7**	**8**	**9**	**10**
	Lp_A,eq,1min [dBA]	51,30	52,23	51,91	51,64	52,86	57,53	51,82	51,41	51,38	52,20
	Lbg [dBA]	39,21	42,33	42,30	44,45	44,12	40,97	42,41	42,30	42,75	44,23
M3	**Delta**	12,09	9,90	9,62	7,19	8,74	16,57	9,41	9,11	8,62	7,97
	Ls [dBA]	51,02	51,76	51,41	50,72	52,24	57,44	51,29	50,84	50,74	51,44
	Lw_A [dBA]	98,28	99,02	98,67	97,98	99,50	104,70	98,55	98,10	98,00	98,71
	Wind Speed [m/s]	**6**	**7**	**8**	**9**	**10**	**6**	**7**	**8**	**9**	**10**
	Lp_A,eq,1min [dBA]	54,03	54,48	54,45	54,16	54,39	53,94	54,48	54,45	54,48	54,71
	Lbg [dBA]	46,08	46,29	46,39	47,14	46,93	46,08	46,29	46,47	46,70	46,99
M4	**Delta**	7,95	8,20	8,06	7,02	7,46	7,86	8,19	7,98	7,78	7,72
	Ls [dBA]	53,27	53,77	53,72	53,20	53,53	53,17	53,76	53,70	53,69	53,90
	Lw_A [dBA]	100,95	101,45	101,39	100,88	101,21	100,85	101,44	101,38	101,37	101,58
	Wind Speed [m/s]	**6**	**7**	**8**	**9**	**10**	**6**	**7**	**8**	**9**	**10**
	Lp_A,eq,1min [dBA]	53,05	54,41	54,20	53,87	54,14	52,86	54,33	54,02	53,64	53,82
	Lbg [dBA]	44,80	45,94	46,65	46,89	47,02	44,80	45,94	46,65	47,00	47,06
M5	**Delta**	8,24	8,46	7,55	6,98	7,13	8,06	8,38	7,37	6,64	6,76
	Ls [dBA]	52,34	53,74	53,36	52,89	53,21	52,13	53,64	53,14	52,58	52,79
	Lw_A [dBA]	99,90	101,30	100,92	100,45	100,77	99,69	101,21	100,70	100,14	100,35
	Wind Speed [m/s]	**6**	**7**	**8**	**9**	**10**	**6**	**7**	**8**	**9**	**10**
	Lp_A,eq,1min [dBA]	51,05	52,40	52,37	51,99	53,10	50,97	52,57	52,58	52,33	52,86
	Lbg [dBA]	42,50	43,67	44,19	44,09	45,37	42,50	43,67	43,95	44,07	44,28
M6	**Delta**	8,55	8,73	8,17	7,91	7,73	8,47	8,90	8,63	8,26	8,58
	Ls [dBA]	50,40	51,77	51,65	51,22	52,29	50,30	51,97	51,94	51,63	52,21
	Lw_A [dBA]	97,66	99,03	98,91	98,49	99,55	97,56	99,23	99,20	98,89	99,47

Appendix B Uncertainty calculation

Sum	$\sum (y - y_{est})^2$	6,0
Amount		55
Sum/(N-2)	$\frac{\sum (y - y_{est})^2}{N-2}$	0,11
Standard error of Laeq (Sum/(N-2))^(1/2)	$\sqrt{\frac{\sum (y - y_{est})^2}{N-2}}$	0,34
Max difference		0,9

Table. 9 Example of the analysis of uncertainty conducted on the data from reference position.

	x^4	**x^3**	**x^2**	**x**	**C**
Total noise	0,0104	-0,2066	0,7259	6,5882	18,237
	y		**y_est**	$(y - y_{est})^2$	
	LAeq	**Wnd,**	**Calculation**	**difference^2**	
14:18:01	54,43342	7,88	54,2	0,039	
14:19:01	54,37807	7,07	54,1	0,094	
…..	….	….	….	….	

Table. 10 Example of how the calculation is performed

Component		**Uncertainty [dB]**
Standard error of L_{Aeq}	$U_A = \sqrt{\frac{\sum (y - y_{est})^2}{N-2}}$	0,34
Calibration	U_{B1}	0,2
Chain of measurement instruments	U_{B2}	0,2
Acoustically hard board	U_{B3}	0,2
Distance measurement	U_{B4}	0,1
Acoustic impedance of air	U_{B5}	0,1
Meteorological variations (including turbulence)	U_{B6}	0,4
Wind speed (both measured and derived)	U_{B7}	0,3
Wind direction	U_{B8}	0,3
Background	U_{B9}	0,1
Total of systematic errors	$U_C = \sqrt{U_A^2 + U_{B1}^2 + U_{B2}^2 + \ldots}$	0,70
Combined standard uncertainty	$U_C = \sqrt{U_A^2 + U_C^2}$	0,78

Table 11. Uncertainty according to Standard [2]

Appendix C Calibration of Wind screens

The calibration of secondary wind screens was according to a method described in [15].
This measurement of the insertion loss is conducted by simulating the inclination angle with an omni-directional loudspeaker on a stand with the height that simulates the ratio of ±20 % of the reference length (R0) from the wind turbine. The measurements are conducted with pink noise from the loudspeaker which is then corrected for background noise by a measurement of background noise immediately after. The three cases that are used are based on the primary wind screen, a 90 mm foam wind screen in two different versions (a whole sphere and half a sphere) and finally a case without primary wind screen. The calibration for the last case is used as the sound level meters have an internal correction for the primary wind screen. Each case are repeated three times with background measurements in between and then averaged. The difference seen in fig.30 (excl. little ball) is used to calibrate the measurement data for the influence of the secondary wind screen.

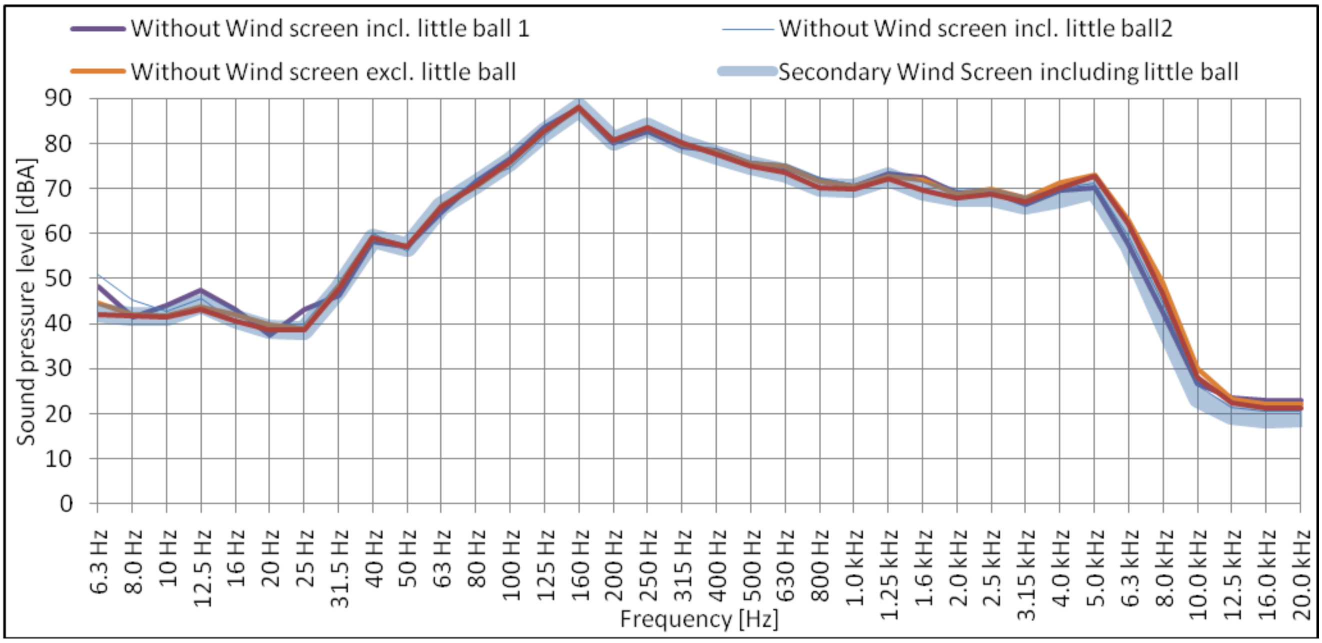


Figure 29. The average sound pressure level for the three cases and without secondary wind screen

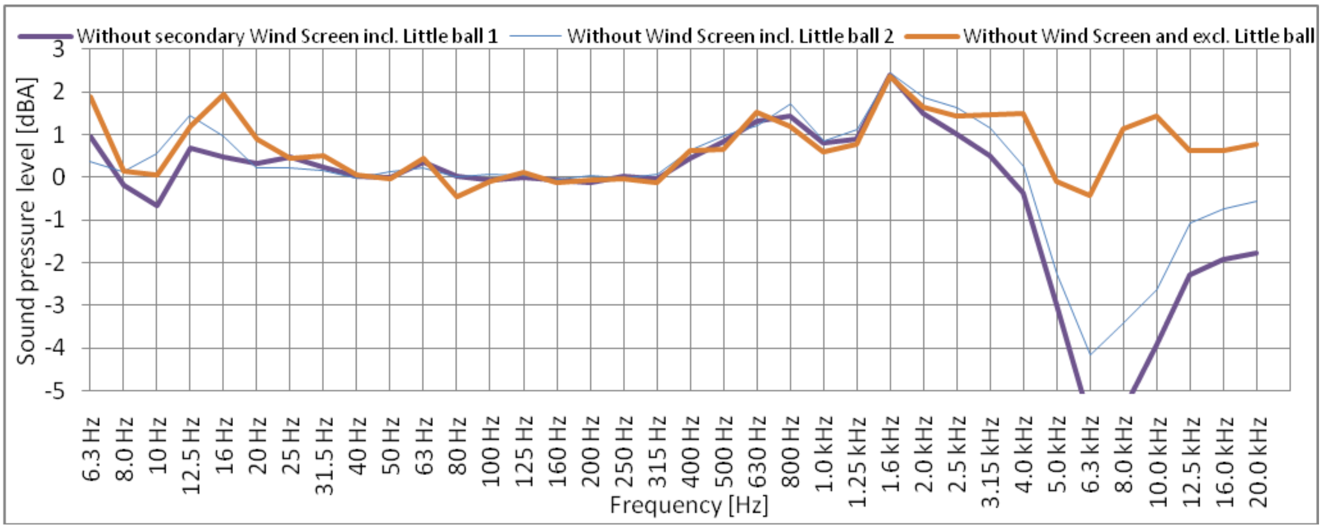


Figure 30. The difference with and without secondary wind screen incl. and excl. primary wind screen

Appendix D Wind turbine noise prediction code (Matlab®)

```
%% ----------------- Wind Turbine Noise Prediction-----------
close all
clear all
clc;
%% Constants
WT=[80 45 1 0.33 3];  % Wind turbine data: Height [m]/ Blade length [m]/
% Foil length [m]/ Rotational speed [Hz] / Angle of attack [°]
Seg=[1:WT(2)];                  %Seperation of blade into segments [m]
dSeg=WT(2)/(length(Seg)+1);     %Width of blade [m]
c=343;                          %Reference speed of sound [m/s]
freq=[100:500:20000];           %Frequency vector [Hz]
u=(2*pi*WT(4)).*Seg;            %Speed depending on segment [m/s]
M=u./c;                         %Machnumber [-]
Re=(u.*WT(3))./(1.78*10^-5);    %Reynolds number [-]
t=[(27.094*M+3.312) (23.43*M+4.651) (72.65*M+10.74) (-34.19*M-13.82)];
%Constants used to derive amplitude correction factors
St=0.02*(M.^(-0.6));            %Strouhal number [-]
Sig=(1.72*WT(3)./sqrt(Re));
%Sig used to derive Strouhal dependent on freq and sound pressure functions
pos=[0:(180/19):180];           %Observer position [°]
dK1=0;
%DeltaK1 a correction factor in the sound pressure function for TE-noise

%% Angle of attack dependency and Amplitude correction factors
%(From reference [5])
if Re<9.52*10^4 x=[0.57; 0.30; -4.31.*log10(Re)+156.3];
elseif 9.52*10^4<=Re<=8.57*10^5 x=[(-9.57*10^(-13)).*(Re-
8.57*10^5).^2+1.13; (-4.48*10^(-13)).*(Re-8.57*10^5).^2+0.56; -
9.*log10(Re)+181.6];
else x=[1.13; 0.56; 128.5]; end;
if Re<=5000 dK1=WT(5)*(1.43*Re-5.29); end;
if WT(5)<t(2)-t(1); K2=-1000; elseif t(2)-t(1)<=WT(5)<=t(2)+t(1)
K2=sqrt(t(3).^2-(t(3)./t(1)).^2 .*(WT(5)-t(2)).^2+t(4)); else K2=-12; end;
if WT(5)<1.33 St_2=St; else St_2=St*10^(0.0054*(WT(5)-1.33)^2); end;
%% Spectral shape functions (From reference [5])
for m=1:length(freq)
St_f(m,:) =(freq(m).*Sig)./u;%Strouhal definitions that are non-dimensional
St_a(m,:)=abs(log10(St_f(m,:)./St)); %Describes oscillating flow mechanisms
St_b(m,:)=abs(log10(St_f(m,:)./St_2));
for n=1:length(Seg)
ac=[St_a(m,n) x(1)]; %Spectral shape functions with boundaries from ref [5]
bc=[St_b(m,n) x(2)];
for o=1:2
if ac(o)<0.204 ai(m,n,o)=sqrt(67.552-886.788*ac(o)^2)-8.219;
bi(m,n,o)=sqrt(16.888-886.788*bc(o)^2)-4.109;
elseif 0.204<=ac(o)<=0.244 ai(m,n,o)= -32.665*ac(o)+3.981;
else ai(m,n,o)=-142.795*ac(o)^3+103.656*ac(o)^2-57.757*ac(o)+6.006;
if 0.13<=ac(o)<=0.145 bi(m,n,o)= -83.607*bc(o)+8.138;
else bi(m,n,o)=-817.81*bc(o)^3+355.210*bc(o)^2-135.024*bc(o)+10.619; end;
end;
if ac(o)<0.13 ax(m,n,o)=sqrt(67.552-886.788*ac(o)^2)-8.219;
elseif 0.13<=ac(o)<=0.321 ax(m,n,o)= -15.901*ac(o)+1.098;
else ax(m,n,o)=-4.669*ac(o)^3+3.491*ac(o)^2-16.699*ac(o)+1.149; end;
if bc(o)<0.10 bx(m,n,o)=sqrt(16.888-886.788*bc(o)^2)-4.109;
elseif 0.10<=bc<=0.187 bx(m,n,o)= -31.330*bc(o)+1.854;
else bx(m,n,o)=-80.541*bc(o)^3+44.174*bc(o)^2-39.381*bc(o)+2.344; end; end;
end; end;
```

```
for m=1:length(freq)
    for n=1:length(Seg)
       aInt(m,n)=(-20-ai(m,n,2))/(ax(m,n,2)-ai(m,n,2));
       bInt(m,n)=(-20-bi(m,n,2))/(bx(m,n,2)-bi(m,n,2));
       A(m,n)=ai(m,n,1)+aInt(m,n)*(ax(m,n,1)-ai(m,n,1));
       B(m,n)=bi(m,n,1)+bInt(m,n,1)*(bx(m,n,1)-bi(m,n,1));
end; end;
%% Relative observer location and Sound pressure calculation
for i=1:length(pos)
X=cos(deg2rad(pos(i)))*2*WT(2)*5;
%Observer position as a spherical coordinate
Y=sin(deg2rad(pos(i)))*2*WT(2)*5;
    for E=1:360;
    Azi=deg2rad(E);
    xyz=[X Y-Seg.*sin(Azi) -WT(1)-Seg.*cos(Azi)]; %Cartesian coordinate
    D=sqrt(xyz(1)^2+xyz(2)^2+xyz(3)^2); %Distance to observer
    Direc=(2.*(sin((pi-
acos((Y.*cos(Azi)+WT(1).*sin(Azi))./D))./2)).^2.*(sin(atan(X./(Seg-
Y.*sin(Azi)+WT(1)*cos(Azi))))).^2)./((1+M.*cos((pi-
acos((Y.*cos(Azi)+WT(1).*sin(Azi))./D)))).*(1+(M - 0.8.*M .* cos((pi-
acos((Y.*cos(Azi)+WT(1).*sin(Azi))./D)))).^2));
    SPL_store_1=0;
%Direc is the directivity function for trailing edge noise ref [5]
    SPL_store_2=0;
%SPL_store, stores sound pressure levels every execution of the forloop
    for ii=1:length(freq)
    SPL_obs(ii,:)=10*log10(10.^((10*log10((Sig.*M.^5.*dSeg.*Direc)./D^2)+
B(ii,:)+K2)./10) + 10.^((10*log10((Sig.*M.^5.*dSeg.*Direc)./D^2) +
A(ii,:)+(x(3)-3) + dK1)./10) +
10.^((10*log10((Sig.*M.^5.*dSeg.*Direc)./D^2) + A(ii,:)+(x(3)-3))./10));
    SPL_store_1=10.^(SPL_obs(ii,:)./10)+ SPL_store_1;
%SPL_obs sound pressure at the observer from SPL functions given in ref [5]
    SPLeq=10*log10(SPL_store_1);
    if ii<=length(SPLeq)
    SPL_store_2 = 10.^(SPLeq(ii)./10)+ SPL_store_2;
    end
end
SPLeq_store(E)=10*log10(SPL_store_2);
if E<121 SPL_1(E)=SPLeq_store(E);
%Summing up the sound pressure level from all three blades to one SPL-value
elseif ((120<E) && (E<241))
SPL_2(E-120)=10*log10(10^(SPLeq_store(E-120)/10));
elseif ((240d<E) && (E<361))
SPL_3(E-240)=10*log10(10^(SPLeq_store(E-240)/10));
end
end
for iii=1:(max(E)/3)
SPL_Sum(iii)=10*log10(10^(SPL_1(iii)/10)+10^(SPL_2(iii)/10)+10^(SPL_3(iii)/
10));
end
SPL_total(i)=Mean(SPL_Sum);
SPL_total(2*length(pos)+1-i)=Mean(SPL_Sum);
%Repeating half the directivity pattern for the other side,
% assuming symmetry
end
plot_rad=deg2rad([0:(360/39):360]);
polar(plot_rad,SPL_total);
title('Directivty')
```