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Wind Turbine Sound Propagation in the Atmospheric Boundary Layer

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Abstract

Wind turbines have grown both in size and number in the past decades. The taller turbines has made it possible to place them in forest areas which is fortunate for a country like Sweden with lots of forest. An issue with wind turbines is the sound they produce. The sound mainly comes from the rotor blades when they pass through the air. The sound heard some distance away from the turbine is sometimes masked by ambient background noise such as wind induced sound in the vegetation, but this is not always the case. Noise concerns among some people living in the vicinity of wind turbines are sometimes raised. Sound propagation models are used to predict the wind turbine sound level at certain distance. It is important that these models are accurate. Sound propagation is greatly influenced by the meteorological conditions. These conditions change over the day and year and vary a lot depending on the terrain conditions. In the past, large meteorological propagation effects have been found for sound sources close to the ground. Higher elevated sources like wind turbines have not been studied as much. One reason for this is that wind turbines are a relatively new sound source.

In this thesis the meteorological influence on the wind turbine sound propagation is studied. Continuous simultaneous acoustic and meteorological measurements are performed at two different wind turbine sites during two years to capture all variations in the weather. The two sites are covered by forest, one is flat and the other has shifting terrain. The sites are representative for many locations in Sweden and around the world. The differences between the measured and expected wind turbine sound levels are established for different meteorological categories. The median of all deviations within each meteorological category is then compared. During no snow cover conditions the variation of the median under different meteorological conditions is 6 dBA and during snow cover the variation of the median is 14 dBA. The variations are due to the combined effect of refraction, ground conditions and terrain shape. The deviations from an expected value are seen for all octave bands from 63 Hz to 1000 Hz but are found to most distinct at low frequencies of around 125 Hz. Meteorological effects starts to be important somewhere between 400 m and 1000 m from wind turbines.

The characteristic "swish" sound from wind turbines are also studied in this thesis. The swish sound or as it is also called, the amplitude modulated sound, is found to be more common under some meteorological conditions such as temperature inversions and downwind conditions. A metric for detection of amplitude modulation duration and strength is proposed. Amplitude modulation, is according to some, the reason why wind turbine sound is perceived as more annoying than other typical environmental sounds at the same sound level. The swishes probably increase the probability to hear the wind turbine sound in presence of other background noise.

Sammanfattning

Vindkraftverk har ökat både i antal och storlek under de senaste decennierna. Högre navhöjder har gjort det möjligt att placera verken i skogsmiljö, vilket är fördelaktigt för ett land som Sverige, med mycket skog. Vindkraftverk producerar ljud. Detta kommer framförallt från vingarna då de skär genom luften. Vindkraftljudet är ibland dolt av naturliga bakgrundsljud men detta är långt ifrån alltid fallet. Människor som bor i närheten av vindkraftverk klagar ibland på ljudet från dessa. Ljudutbredningsmodeller används för att beräkna vindkraftljudnivån på ett visst avstånd från ett verk. Det är viktigt att dessa är precisa och gör riktiga utsagor så att planeringsunderlaget innan vindkraftverk byggs blir riktigt. Det har visat sig att meteorologiska förhållanden har en stor påverkan på ljudutbredning. De meteorologiska förhållandena varierar under dygnet och året. Terrängen har också betydelse för denna variation. Tidigare har stora meteorologiska variationer i ljudutbredningen hittats för ljudkällor nära marken. Högre ljudkällor som vindkraftverk har inte studerats lika mycket vilket kan bero på att vindkraftverk är en relativt ny ljudkälla i samhället.

Detta arbete syftar till att öka kunskapen om hur meteorologin påverkar ljudutbredningen från vindkraftverk. Samtidiga kontinuerliga långtidsljudmätningar har utförts vid två vindkraftparker. Båda platserna har mark täckta av skog även om en del öppningar i skogen förekommer på grund av kalhyggen och myrmark. Den ena mätplatsen är platt medan den andra har en mer varierande terräng. Skillnaden mellan uppmätta och förväntade vindkraftljudnivåer bestäms för olika meteorologiska kategorier. Medianen av alla avvikelser inom varje kategori jämförs sedan. Vid barmark varierar denna median med 6 dBA under olika meteorologiska förhållanden och vid snötäcke är variationen av medianen 14 dBA. Dessa variationer antas bero på en kombinerad effekt av refraktion, markens mjukhet och topografins utseende. Avvikelsen i förväntad ljudnivå syns för alla ljudfrekvenser mellan tersbanden 63 Hz och 1000 Hz men är tydligast för låga frekvenser kring 125 Hz. De meteorologiska effekterna börjar märkas någonstans mellan 400 m och 1000 m från vindkraftverk.

Det karakteristiska svischande ljudet från vindkraftverk studeras också i denna avhandling. Svischljud eller amplitudmodulation som det också kallas, visar sig vara vanligare under vissa meteorologiska förhållanden som t ex vid temperaturinversion och medvindsförhållanden (vind från vindkraft mot mottagare). Amplitudmodulation är enligt vissa en av förklaringarna till att vindkraftljud uppfattas som mer störande än andra vanliga ljudkällor vid samma ljudnivå. Svischljudet gör det sannolikt också lättare att uppfatta vindkraftljudet bland andra ljud som t ex lövprassel. En metod för att bestämma amplitudmodulationens varaktighet och styrka föreslås i avhandlingen.

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Öhlund O and Larsson C, 2014. Meteorological effects on wind turbine sound propagation *Submitted for publication in Applied Acoustics*

II Larsson C and Öhlund O, 2014. Amplitude modulation of sound from wind turbines under various meteorological conditions *The Journal of the Acoustical Society of America, 135(1), January 2014*

In paper I the author had the main responsibility for analyzing the data and writing the article. The measurement stations setup were designed together with the co-author.

In paper II the author analyzed the data and had a shared responsibility for writing the text.

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1. Introduction

Anthropogenic emission of carbon dioxide and their impact on global warming has drawn a lot of attention in the past decades. This has motivated countries to try to decrease their carbon emissions. One way to do this is to use environmental friendly energy sources like wind turbines (WTs). The number of WTs has increased rapidly in Sweden during the last year and an ambitious goal of 30 TWh wind power energy year 2020 has been introduced. In the end of 2012 Sweden had 2385 turbines which corresponded to 4.4 % of the total electricity produced in the country [1]. Some other countries have come even longer. For example, Denmark produces over 20 % of its electricity from wind. Many people are positive to wind energy. However WTs sometime raise concerns in the local environment. It has been found that the sound that the turbine produces is a source of disturbance [2, 3, 4]. WTs produce sound when the rotor is moving through the air and sound also comes from the machinery in the hub of the WTs today. The main sound source is the rotor blades. Even if the actual sound level at certain distance from a wind turbine (WT) is relatively low, the sound could be perceived as annoying. It has been demonstrated that people get more annoyed by WT sound than railway noise or traffic noise at the same sound level [4]. One reason for this could be the sound characteristics of WT sound, which is analysed in Paper II. The sound is amplitude modulated with time, which is often referred to as a rhythmic "swish" or "thumbing" sound [5, 6]. The physical mechanism resulting in different sound characteristics depending on observer locations and time is not fully understood.

The WT sound topic can be divided into three categories; the sound emission at the source, the sound propagation in the atmosphere and the sound immission at a receiver, see fig. 1.1. These are often linked- in this study for example we could not know how sound propagates if we did not know the sound emitted by the source and the sound level at an immission point. Sound propagation has been studied for a long time. The speed of sound equation goes back to the days of sir Isaac Newton. At the end of the 19th century the main purpose was to make the sound audible as long as possible. Ships and lighthouses used signals in the fog to warn ships around. Today the mission is often the opposite. A shift in the soundscape came with the car. Road traffic is today the main noise source in many countries. Environmental problems today call for studies of how to reduce sound. The emitted sound from WTs has been investigated and it has been concluded that most of the sound perceived at a distance comes from the turbine blades [7]. The WTs also show a

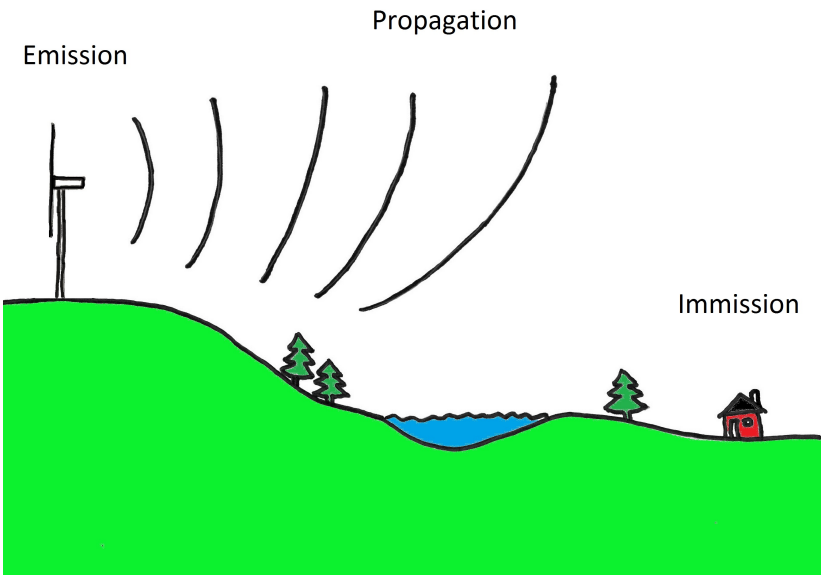

Figure 1.1. A schematic figure of different wind turbine sound branches.

horizontal directivity pattern, with less sound energy emitted in the rotor plane [8]. The psycho-acoustical field is coupled to the immission point and deals with how people perceive a certain WT sound level and when it can be heard in the presence of natural ambient sounds. This thesis is focused on the sound propagation part and how the sound travels through the atmospheric boundary layer. It is crucial to include as much knowledge as possible about the sound source to avoid attach effects from the sound source as propagation effects.

In the planning process sound propagation models are used to predict the WT sound. One of the issues today is to derive accurate models to predict the wind turbine sound. The difficulty comes from the weather influence on the sound propagation. These effects have been studied for sound sources closer to the ground [9, 10]. For higher elevated sound sources like WTs less is known on the meteorological influence on the propagation. The meteorological parameters have a diurnal and daily variation. They also change differently with height depending over which surface you are looking i.e. over forest, over sea or over grassland. Sound propagation conditions could therefore be different over these different ground types.

To capture all the different propagating conditions during a year, long time sound measurement and meteorological measurements are needed. Unattended sound measurements are challenging due to ambient sound in the natural environment. These could mask the WT sound [11, 12, 13]. Common natural ambient sounds are vegetation induced sound, sound from breaking sea waves

and bird song. Sound from traffic and human activities could also disturb acoustic measurements, however the two measurement sites used in this work are very sparse populated.

The main focuses in this research project have been:

- Increase the knowledge of how sound propagate over forest and heterogeneous terrain.
- Investigate how variations in the meteorological parameters influence the sound propagation during different parts of the year.

2. Sound propagation

Examples of noise issues can be found far back in the history. The romans prohibit wheeled traffic from the Forum because of the noise it caused [14]. Sound and the transmission of it is even more adequate today when human made sound is more common than ever in history. In 1726 sir Isaac Newton came up with an expression of the speed of sound from the compressibility and density of air. Newton assumed that the compression of the air took place isothermally, which was incorrect. This was later in 1738 corrected by Laplace who included the adiabatic compressibility of air in the sound speed equation. The Newton- Laplace equation is,

$$c_{adiabatic} = \sqrt{\gamma \cdot \frac{P}{\rho}}, \tag{2.1}$$

where $c_{adiabatic}$ is the adiabatic sound speed, γ is the ratio of specific heats of a gas at a constant pressure to a gas at a constant volume, P is the pressure and ρ is the density. The formula from more than two hundred years ago is within 0.5 % of the best modern value. If the effect from humid air from Gutenberg [15] and wind is included [16], the sound speed in the source to receiver transect is calculated as the effective sound speed,

$$c(z) = \sqrt{\gamma R_{gas} T(z)} \left(1 + 0.14 \frac{p(z)}{P(z)}\right) + u(z) \cdot e_t, \tag{2.2}$$

where R_{gas} is the gas constant for dry air (J K^{-1} kg^{-1}), T is the temperature (K), p is the water vapour pressure (Pa), u is the wind speed (ms^{-1}) all given at a height of z (m). e_t is the horizontal unit vector pointing along the propagation transect. Equation 2.2 is valid for relatively small elevation angles where the height difference between source and receiver is much smaller than the direct propagation path [16].

The meteorological influence on sound propagation has been studied for a long time. The most significant effects are refraction, atmospheric absorption and turbulent scattering. Temperature and wind speed always change with height in the lower atmosphere, but in the horizontal over flat terrain, the change is smaller. Vertical temperature and wind gradients have a great influence upon the sound propagation due to refraction phenomena. The radius of curvature, R, can be used to express how much a sound ray is going to be bent and can be expressed as [17]:

$$R = \frac{1}{\frac{\partial c}{\partial z} \cdot c/cos(\theta)}, \tag{2.3}$$

where $\partial c/\partial z$ is the vertical gradient of the sound speed (s^{-1}) and θ is the sound ray propagation angle ($^\circ$) where a positive θ is above the horizontal plane and negative θ is under the horizontal plane. For positive R the sound rays are bent downwards toward the ground (concave toward the ground). For negative R the sound rays bend upwards (convex) from the ground. Smaller values of R indicates stronger refraction and for a certain θ they occur when $\partial c/\partial z$ is larger. The sound speed gradient depends strongly on the wind speed and temperature differences with height as seen in equation 2.2.

When a sound wave travels through the air a small fraction of the energy is converted into heat when the air molecules start to vibrate. This is called molecular absorption or atmospheric absorption. There are time delays in the energy conversion and these delays are associated with the amount of triatomic molecules, especially water vapour molecules. The damping effect increases with sound frequency and distance traveled and is dependent on the relative humidity, air temperature and air pressure. Atmospheric absorption has been studied in detail in laboratory environment. An international standard giving the absorption for different conditions is available [18].

Turbulence in the atmospheric boundary layer produces random distortions of the sound wave front. Temperature and wind speed fluctuations will scatter sound into sound shadow zones and cause fluctuations in the phase and amplitude of the sound waves. In an atmosphere without turbulence a spherical sound wave from a point source will have the same phase and amplitude at a certain distance from the source. In the presence of turbulence, this will not be the case. This can change the interference between direct rays reaching the microphone and reflected ones, thus changing the interference pattern. The effect of turbulence on the sound field increases with propagation distance. The behavior of sound wave phase and amplitude in a turbulent atmosphere has been studied close to the ground [19]. Measurements taken over time periods of around 10 minutes often smooth out the random fluctuations in instantaneous sound levels.

Outdoor sound propagation is always influenced by the ground. Sound rays will reach a receiver in two ways. One direct ray from source to receiver which has no contact with the ground and one reflected ray from the ground surface. If the path length difference between the direct and reflected ray is half a wavelength of the sound wave, destructive interference occur. The reflected sound wave could also change phase depending on the incidence angle of the wave towards the ground and the properties of the ground. A review article by Attenborough [20] describes the ground effect. The properties of the ground are described by the ground impendence which can be expressed in term of the flow resistivity of the ground and has been studied by several

authors [21, 22, 23]. The simple case with a plane wave at normal incidence toward the ground, will result in higher attenuation of higher sound frequencies than lower sound frequencies [21]. The exact phase and amplitude relationships between direct and reflected rays will be destroyed if the propagation distance is large, atmospheric turbulence is present and sound rays are bent by refraction. This is often the case for WT sound measurements.

2.1 Meteorology

As seen in equation 2.2 the effective sound speed is dependent mainly on the temperature and the wind speed. To calculate the important effect of refraction, knowledge of how the temperature and wind speed behave at different heights above the ground is necessary. Instantaneous values of these parameters often change rapidly due to atmospheric turbulence. In the coming part the mean profiles over 10 minutes will be used.

The atmospheric boundary layer is the lowest part of the troposphere which is directly influenced by the earth surface. The layer will react to changes in the surface temperature on a relatively short time scale. The flow in the atmospheric boundary layer is always to some degree turbulent due to the mechanical friction against the ground and heat transfer between the ground and the atmosphere. The height of the boundary layer will vary from just hundred meters to one or two kilometers depending on season and time of day. The lowest 10 % of the boundary layer is called the atmospheric surface layer. Meteorologists have been able to develop empirical expressions for the vertical profiles of temperature and wind in the surface layer. The expressions are based on so called similarity relations which give a realistic representation of how the parameters vary under different conditions. The similarity theory is valid for flat and homogeneous areas. Above the surface layer knowledge about the large scale weather situation need to be included to get the profiles.

The pressure in the atmosphere decreases with increasing height above the ground. This will result in an air temperature decrease with height in the adiabatic approximation. The potential temperature is defined as:

$$\theta = T\left(\frac{P_0}{P}\right)^{R_{gas}/c_p}, \tag{2.4}$$

where P is the pressure an air parcel have at some altitude, P_0 is a reference pressure, usually 1000 hPa and c_p is the specific heat capacity at a constant pressure. The potential temperature is the temperature an air parcel would have if it is moved adiabatically to the 1000 hPa level. The sign of $\partial\theta/\partial z$ is very important in meteorology and is a measure of the atmospheric stability. On clear summer days $\partial\theta/\partial z$ usually is negative above a land surface. The warmer air close to the ground will move upwards and the atmosphere is called unstable. On clear nights, $\partial\theta/\partial z$ are often positive. The ground is

radiative cooled and the air above it is cooled by the ground. The air becomes denser the air above. In this case the atmosphere is called stable and vertical movements of air are damped. Regarding the sound speed, the air temperature T is the important parameter rather than θ. In a dry adiabatic atmosphere the temperature will decrease with 1 °C for every 100 m increase in height.

The wind velocity in the surface layer depends on the temperature profile. It also depends on the roughness of the ground. Higher roughness will slow down the wind close to the surface due to more friction. At the ground surface the wind speed is always zero. The wind direction will vary with height in the atmospheric boundary layer due to the rotation of the earth and the pseudo-force called the Coriolis force. A theoretical value of the wind veer within the Ekman layer (the layer from the top of the surface layer to the top of the boundary layer) is 45° [24]. Observed values are often lower. A mean wind veer of roughly 10° during stable conditions between 40 m and 140 m height above a forest have been reported from Arnqvist [25]. The variation in wind direction with height from the ground to 140 m above the canopy can be as much as 40° [25] during stable conditions. The wind speed profile in the atmospheric surface layer could with similarity theory be obtained through,

$$\phi_m = \frac{\kappa z}{u_*}\frac{\partial \bar{u}}{\partial z}, \tag{2.5}$$

$$\phi_h = \frac{\kappa z}{\theta_*}\frac{\partial \bar{\theta}}{\partial z}, \tag{2.6}$$

where ϕ_m is the dimensionless vertical gradient of wind speed, ϕ_h is the dimensionless vertical gradient of temperature, κ is the von Karman constant, u_* is the friction velocity, θ_* is a characteristic temperature and $\bar{u}$ is the mean wind speed. The friction velocity is defined as,

$$u_* = \sqrt{-\overline{u'w'}}, \tag{2.7}$$

where $\overline{u'w'}$ is the kinematic momentum flux. The temperature θ_* is defined as,

$$\theta_* = \frac{-\overline{w'\theta'}}{u_*}, \tag{2.8}$$

where $\overline{w'\theta'}$ is the kinematic heat flux at the ground. The dimensionless wind speed and temperature gradients are dependent on the stability of the atmosphere. Expressions for ϕ_m and ϕ_h have been proposed by several meteorologists [26, 27, 28]. The expressions from Högström [28] for unstable atmosphere are,

$$\phi_m = (1 - 19.3z/L)^{-1/4}, \tag{2.9}$$

$$\phi_h = (1 - 12z/L)^{-1/2}, \tag{2.10}$$

and for stable atmosphere,

$$\phi_m = 1 + 4.8z/L, \tag{2.11}$$

$$\phi_h = 1 + 7.8z/L, \tag{2.12}$$

where L is the Obukhov length, which could be interpreted as the height at which the thermal and mechanical production of turbulence is of the same size. The definition of the Obukhov length is,

$$L = \frac{\bar{\theta} {u_*}^3}{\kappa g(\overline{w'\theta'})}, \tag{2.13}$$

where g is the gravitational acceleration. In the field values of the heat fluxes are not easily determined. An easier way to determine the value of z/L is to use the expression [26],

$$\frac{\phi_h}{{\phi_m}^2}\frac{z}{L} = Ri, \tag{2.14}$$

where Ri is the Richardson number, defined as,

$$Ri = \frac{g}{T}\frac{\partial\theta}{\partial z} \Big/ \left(\frac{\partial u}{\partial z}\right)^2. \tag{2.15}$$

The Richardsons number is easier to obtain out of gradients in temperature and wind speed from an ordinary meteorological mast. Equation 2.15 will give a value of the Richardson number which through equation 2.14 gives a value of z/L. This can then be used in eq. 2.11, 2.12, 2.9 or 2.10 which gives a ϕ_m or a ϕ_h that can be used in eq. 2.5 or 2.6 integrating up to a certain height to get the wind speed or temperature there. The similarity theory could also be used over a forest canopy if a displacement height d and a correction function is used [25].

3. Measurement sites and instrumentation

Two measurements sites have been used in this study. The Ryningsnäs site is located in southern part of Sweden, close to Målilla and the Dragaliden site is located in northern Sweden close to Koler outside Piteå. Both WT sites are located in rural environment and sparsely populated. Both sites are covered by heterogeneous forests with lot of clearings. A system with a Norsonic Nor140 sound level meter and an outdoor microphone were placed at 1.5 m height above the ground inside the forest at both sites. Measurements according to the standard procedure [29] at ground level were not possible due to snow cover in the winter season. The instrument measures the sound spectrum in 1/3 octave band levels with midband frequencies from 6.3 Hz to 20 kHz. At each site at least one high (at least 120 m high) meteorological mast were available in the vicinity, which collects meteorological data simultaneously with the acoustical data. Besides an 18 m high mast was also present close to the microphone which gives wind speed, wind direction and temperature at four different levels inside the forest. Air pressure and relative humidity is given at 1.5 m above the ground. Both the acoustical stations and and short meteorological masts are powered by grid of long cables through the forest.

3.1 The Ryningsnäs site

Two Nordex 2.5 MW WTs stand in the relatively flat landscape. The hub heights are 100 m and 80 m. The acoustical measurements are taken 410 m to the east from the higher WT and 580 m to the northeast of the shorter WT. A 140 m high meteorological mast close to the WTs gives wind speed at seven different heights between 25 and 140 m. Temperature is given at three levels between 25 m and 140 m. To the southeast of the turbines there is a large clearing ranging from 90 to 180°. The mature trees in the area is approximately 20 to 25 m high.

3.2 The Dragaliden site

At the Dragaliden site twelve Enercon 2 MW WTs are placed on the hill of Dragaliden. The hill is approximately 100 m higher than the lower spots in the area. The turbines are placed in two rows in the northwest to southeast direction. The turbines have hub heights of 108 m or 138 m. The taller turbines are

Figure 3.1. One of the WTs at the Dragaliden site a day in April 2011 (Photo C. Larsson).

number three and six in the northern row counted from the west. The distance from the acoustical measurement station to the closest turbine is 1060 m and to the turbine furthest away 1970 m. The microphone is placed northeast of the WTs, perpendicular to the WT rows. The tree height is around 15 m in the surroundings. Four meteorological masts with height between 120 m and 150 m are available within 20 km of the microphone. The tall masts are placed on hills with similar shape as the Dragaliden site. Wind speed and wind direction is gathered at seven different heights between 40 m and 150 m height. Temperature is given at three different heights between 3 m and 150 m height. The meteorological parameters are assumed to be terrain following and the data from the tall masts are assumed to represent the local conditions around the WTs.

4. Results

In this section the most important methods and results are presented. The first part, based on Paper I, concerns meteorological effects on sound propagation from WTs. Measured WT sound levels are compared with calculated values and the difference is coupled to meteorological conditions. The second part is a summary of the main findings in Paper II and investigates a phenomenon referred to as amplitude modulation (AM) which often is referred to as swish sound. It is investigated if this AM is perceived more often during some meteorological conditions.

4.1 Meteorological effects on wind turbine sound propagation

The acoustical and meteorological measurements were continuous for two years, only with exception for small interruptions. The emitted sound power level from the turbines was obtained from the WT manufacturer's test reports [30, 31]. The expected WT sound pressure level (SPL) at the immission point is calculated assuming spherical spreading from a point source ($1/r^2$ loss, where r is the distance between source and receiver) and the present atmospheric absorption. The deviation from the expected value is assumed to arise from the meteorological effect of refraction and the ground. The relative SPL (ΔL) was defined as the difference between the measured SPL and the calculated SPL,

$$\Delta L = L_{pA} - 10log\sum_{i=1}^{k} 10^{(L_{WA_i}+D_{Ii}-10log(4\pi r_i^2)-\alpha r_i)/10}, \tag{4.1}$$

where L_{pA} is the measured SPL at the immission point, L_{WA} is the emitted sound power level, D_I is the directivity correction [32], r is the distance in meters between source and receiver all for the i:th turbine, and α is the atmospheric absorption coefficient [18] per meter in the current atmosphere. Notice that the term D_I is added here, which was not included in Paper I equation 1, when submitting the paper. This will change the previous results a little.

Measuring WT sound in the presence of natural background is difficult. A number of criteria were set in Paper I to avoid influence from background noise in the WT sound measurements. During a 10 minute measurement WT sound was regarded as the dominant sound source if the following criteria were met:

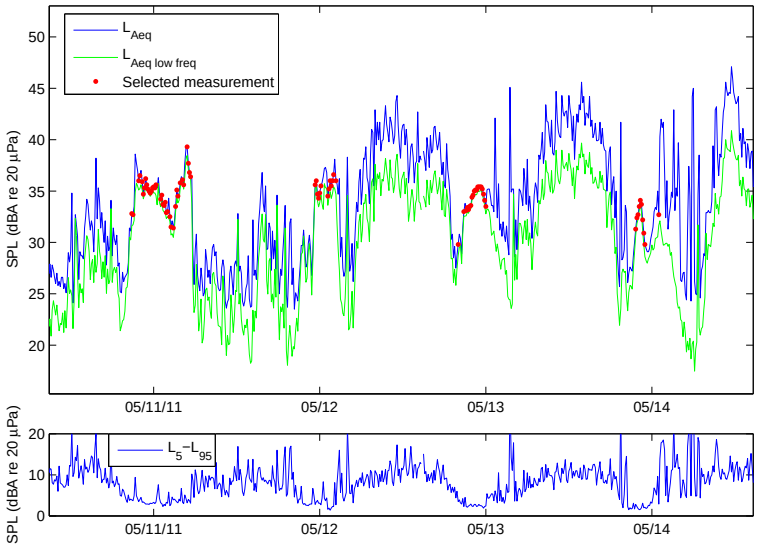

Figure 4.1. Example of acoustic measurement time series at the Dragaliden site during roughly four days in May 2011. The L_{Aeq} calculated from 10 Hz to 20 kHz and $L_{Aeq,low\,freq}$ calculated from 10 Hz to 630 Hz are shown. Selected measurements where WT sound is dominant is indicated by red dots. Bottom frame shows the percentile L_5 minus L_{95}.

a) $L_5 - L_{95} \leq 4$ dBA.

b) The A- weighted $1/3$ octave band sound level from 800 Hz and above should not contribute more than 1.5 dB to the total A- weighted SPL if the total SPL is above 25 dBA.

c) Calculation of free field spreading from every turbine (treated as point sources) contribute to a total SPL of 30 dBA or above in the immission point.

Criterion a) states that if large variations in the sound levels occurs over a time period of ten minutes the measurements is reject. It has empirically been found to work well during all our visits to the different stations. This criterion has been used in a previous work [5] to avoid background influence on 5 minutes WT sound measurements. Criterion b) requires a certain shape of the sound spectrum, which effectively excludes wind induced sound in the vegetation. Criterion c) ensures that the turbines are operating at a certain level. These strict criteria leave us with 7 % and 10 % of the total measurement time to analyse for the Dragaliden site and the Ryningsnäs site respectively. An example of a measurement time series from the Dragaliden site is shown

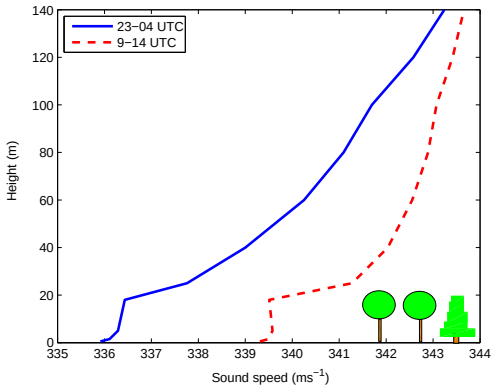

Figure 4.2. Mean measured downwind sound speed profiles during two years for the Ryningsnäs site. Blue line is the night time measurements and red line is the daytime measurements

in fig. 4.1. It can be seen that selected measurements during this part of the year are mostly night-time measurements.

Measurements of the vertical profiles of wind speed and temperature over an open field were compared with profiles within and above a forest in Paper I. It was found that the sharpest gradients in temperature and wind speed for a forest site is above the canopy. For an open field the layer just above the ground usually has the sharpest gradients. For the forest sites a diurnal pattern in the sound speed gradient is often found above the canopy, see fig. 4.2. The measurement period in fig. 4.2 was two years and it is found that night-time profiles in the mean have a sharper sound speed gradient than daytime profiles. The reason for this is the vertical temperature profile variation on days and nights with clear skies, which influences the wind speed profile. This will be important for the WT sound propagation.

The results from the Ryningsnäs site where the sound propagation distance was around 400 and 600 m are shown in fig. 4.3. The sound speed gradient refers to the vertical difference in sound speed at 120 m height and at the ground calculated with eq. 2.2. The transect from the centre of the WT park to the receiver is the direction of interest. No clear meteorological dependence on the relative SPL in fig. 4.3 could be seen. ΔL values are positive (median values 2 - 5 dBA above the free field value). For sound speed gradients close to zero median ΔL values are lower, which is an indication that the directivity index used in eq. 4.1 does not compensate totally for the actual directivity. The difference between no snow and snow cover conditions is very small for positive sound speed gradients. For negative sound speed gradients it is seen in fig. 4.3 that higher ΔL values are obtained for no snow cover conditions.

For longer sound propagation distances at the Dragaliden site a clear effect of refraction and ground properties can be seen in fig. 4.4. Large differences

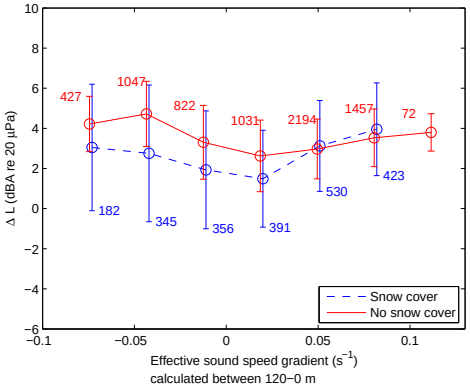

Figure 4.3. Relative SPLs for the Ryningsnäs site, during different refractive atmospheric conditions. The bars indicate one standard deviation of the data and the numbers gives the total number of 10 minute measurements within each bin. The median in each bin is given by circles (o).

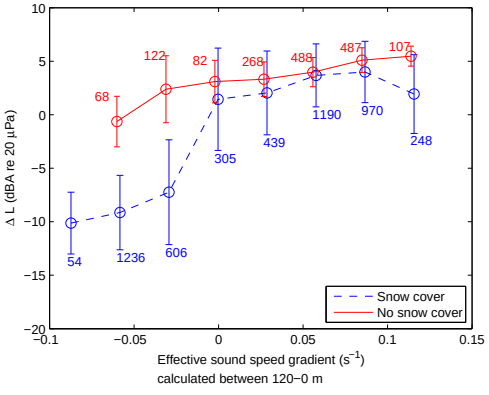

Figure 4.4. Relative SPLs for the Dragaliden site, during different refractive atmospheric conditions. The bars indicate one standard deviation of the data and the numbers gives the total number of 10 minute measurements within each bin. The median in each bin is given by circles (o).

in the median ΔL values are found for snow cover and no snow cover conditions. For no snow cover conditions a variation of 6 dBA in the median is found between different refractive conditions. The corresponding variation for snow cover conditions is 14 dBA. The standard deviations of the data is larger for snow cover than no snow cover which probably has to do with different properties of the snow and if snow is present on the trees or not. It can also be seen from fig. 4.4 that during moderate downward refractive conditions the median ΔL values are similar for the two ground types. The ΔL values in fig. 4.4 are generally high for positive sound speed gradients and low for negative sound speed gradients. In fig. 4.5 the effects can be seen for octave bands between 63 and 1000 Hz. For snow cover conditions the largest variation in the median ΔL depending on the sound speed gradient is 17 dBA and occur for the octave band with centre frequency 125 Hz. For no snow cover conditions the relations are weaker for higher octave bands. At octave band 125 Hz a variation of 14 dBA depending on the sound speed gradient could be detected at no snow cover conditions. At 2000 Hz the WT signal is attenuated a lot by the atmospheric absorption, which explains why we do not see any ΔL dependence upon the sound speed gradient here.

4.2 Amplitude modulation of sound from wind turbines under various meteorological conditions

At the same sound level, WT sound annoys people more than sound from road traffic [2]. The reason for this is not clear. One reason could be the amplitude modulated "swishing" characteristics of the WT sound. A lot of people discuss amplitude modulation (AM) from WTs, but what they really mean with AM is vague. A method for quantifying the amount and strength of AM is proposed in this work. The mechanism creating AM is not fully understood, although some investigations at the sound source have been made [5, 6, 33]. In Paper II it is found that AM of WT sound is more common under specific meteorological conditions. The instantaneous A-weighted 1/3-octave sound pressure level with time weighting fast (F) was sampled at 8 Hz continuous during one year at two immission point near WT parks in Sweden. The method proposed in Paper II for detection of AM consist of a Fast Fourier Transform (FFT) of the time series of A-weighted sound pressure levels (calculated from the 10 - 630 Hz 1/3-octave bands only) for a time window of 15 s. The frequency range was selected because WT sound contains a clear signal in this range. The FFT will generate an amplitude modulation spectrum (AMS) seen in fig. 4.6 to the right, from which the AM modulation strength can be obtained,

$$\mathrm{AMS} \equiv \sqrt{2} * |\mathrm{FFT}(L_{A,F,8\,\mathrm{Hz},15\,\mathrm{s}})|/N, \tag{4.2}$$

where N is the number of samples. Because periods of 15 s are analysed using a sampling frequency of 8 Hz, N becomes 120. The AMS gives the

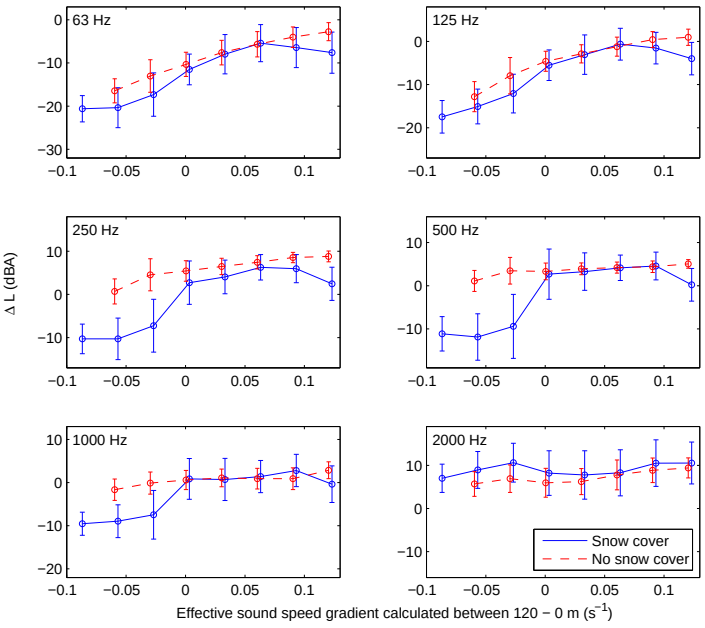

Figure 4.5. Relative SPLs at different octave bands for the Dragaliden site, during different refractive atmospheric conditions. The bars indicate one standard deviation of the data and the numbers gives the total number of 10 minute measurements within each bin. The median in each bin is given by circles (o).

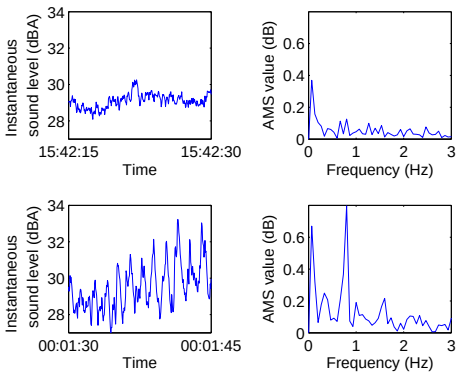

Figure 4.6. Sound level recording from the Dragaliden site on 20 July 2011 at different times of the day, from Paper II. The measurements were made 2.3 kilometer from the closest turbine at the Dragaliden site. The AMS on the right detect periodical patterns at different frequencies from the 15 s periods indicated on the left.

different frequency components of the level variations, and it is independent of the absolute level of the sound; only the relative fluctuations are reflected.

Large WTs often have blade passing frequencies of 0.6 - 1 Hz in operational mode, so the AM factor is defined from the AMS for a given 15 s period:

$$\text{AM factor} \equiv \max[\text{AMS}(f)], \text{within the range } 0.6\,\text{Hz} \leq f \leq 1.0\,\text{Hz}. \quad (4.3)$$

Based on many observations made at both days and nights at the measurement sites and on studies of various AMS, the AM of a 15 s period in Paper II is defined as:

$$\begin{aligned} \text{AM present} &\equiv \text{AM factor} \geq 0.4\,\text{dB}, \\ \text{AM absent} &\equiv \text{AM factor} < 0.4\,\text{dB}. \end{aligned} \quad (4.4)$$

This method efficiently finds signals with specific periodicity and can detect AM in the presence of moderate background noise.

Analysis of one year of continuous sound measurements reveals that AM is more common under some meteorological conditions. In fig. 4.7 the prevalence of AM under specific conditions can be seen. The sound propagation distance between the twelve WTs and the receiver varies between 1060 and 1970 m. AM is more common during downwind conditions which also often correspond well with a positive vertical sound speed gradient in the transect from the center of the park toward the receiver. The suggestion that AM should be more pronounced in cross wind direction [33] was not supported in Paper II. WT sound emitted in cross wind direction is lower than sound emitted in downwind direction due to directivity. This could explain why AM in cross-wind direction is stronger in model run but in reality these fluctuations are difficult to detect. AM is more common during temperature inversions as seen

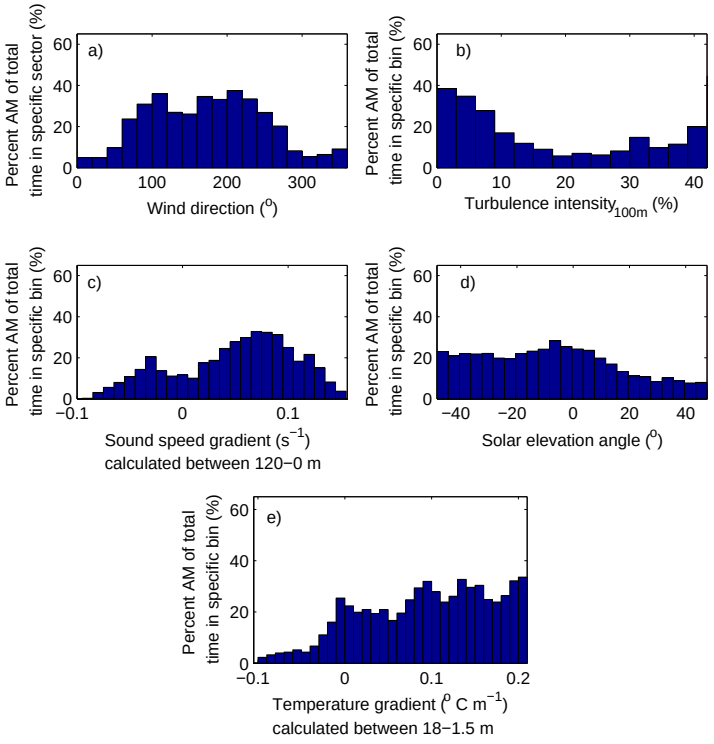

Figure 4.7. Percent of AM (AM measurement time divided by total time) in a specific bin for the Dragaliden site during one year.

in fig. 4.7 e). Temperature inversions occur typically on clear nights with radiative cooling of the surface. In fig. 4.7 d) it is seen that evenings and nights are more associated with AM than daytime. In overall AM is detected between 20 - 30 % of the time WTs are operating depending on distance.

5. Concluding remarks

New WT parks have people that welcome them and people that are opposing them. This is always the case for new infrastructure. Society needs to balance between benefits and drawbacks. In rural areas were quietness often is appreciated, the positioning of new WTs could be sensible and good knowledge of sound propagation is needed. WT sound contribute with low sound pressure levels but is a continuous sound that often persist for long times. Because of the relatively low sound level, background sound levels are often relevant when discussing annoyance. These are mostly lower in rural areas than in more populated areas.

Sweden today has a fixed limit regarding WT sound. A maximum sound level is set that should not be exceeded under specific conditions. People living in the vicinity of WTs often describe how the WT sound levels vary from day to day. Another way to regulate WT sound is to allow the sound level to exceed a certain value some percentage of the time. This could be more appropriate when dealing with sound levels that vary much. The variation in WT sound transmission is also one main finding of this thesis - the WT sound level at some location far from the turbines will be dependent on the meteorological conditions. Of course the emitted sound from the turbines is also dependent on the weather conditions- the turbines will not make any sound if there is no wind. But in this work it is found that the transmission of the WT sound also is dependent on the meteorological condition. Assuming spherical spreading of the sound energy from the source, accounting for the atmospheric absorption and the directivity of the source, the transmission loss to the receiver could deviate from what you expect it to be. This deviation is caused by an interaction between refraction, ground properties and terrain shape. The variation width of your actual transmission loss could be 6 dBA for no snow cover conditions and 14 dBA for snow cover conditions if you do many measurements. One reason for the larger variation for snow cover conditions is probably the increased attenuation of the reflected sound waves from the snow cover at grazing angle of incidence. The sound speed profile in the propagation direction will be important for the sound transmission. Gradients in the sound speed will bend the sound rays. If the ray travels in a layer with large sound speed gradient longer, the refraction will be larger than if the ray enters the layer with a large incidence angle and quickly go through the layer. For horizontally rays from the WT, the gradient at the hub height will be very important. For receivers at long distances the sound speed gradient close to the ground will also be very important because the ray could travel almost horizontal here. The wind direction will change with altitude in the atmospheric boundary layer. Under very

stable conditions the wind veer can be large. This will influence the sound speed profile and could create a sound speed gradient close to the hub height in the crosswind direction.

In this study WT sound emissions are taken from manufacturer's test reports. These are carried out carefully following standard procedures. Even so, the reports have a total measurement uncertainty of the sound power level of 2.2 dBA. This need to be kept in mind when discussing actual WT sound levels at a certain distance. The variation width in the sound level during different meteorological conditions will not be influenced much by the sound emission uncertainty.

In this thesis it is concluded that AM sound from the WTs is more common under specific meteorological conditions such as downwind conditions and temperature inversions. Ambient sound level will also be important, in high ambient levels the WT signal will be lost and not detected as AM. AM of WT sound is detected roughly 20 - 30% of the time depending on distance from the turbines. The amount of time AM is detected is probably also a rough estimate on when WT sound is clearly heard in the presence of natural background sounds.

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