KTH VETENSKAP OCH KONST

KTH Engineering Sciences

Wind Turbine Noise and Natural Sounds-

Masking, Propagation and Modeling

Karl Bolin

Doctoral Thesis

Stockholm 2009
Kungliga Tekniska Högskolan
School of Engineering Sciences
Department of Aeronautical and Vehicle Engineering
The Marcus Wallenberg Laboratory for Sound and Vibration Research

Postal address
Royal Institute of Technology
MWL / AVE
SE-100 44 Stockholm
Sweden

Visiting address
Teknikringen 8
Stockholm

Contact
Tel: +46 8 790 92 02
Fax: +46 8 790 61 22
Email: kbolin@kth.se

Akademisk avhandling som med tillstånd av Kungliga Tekniska Högskolan i Stockholm framläggs till offentlig granskning för avläggande av teknologie doktorsexamen tisdagen den 26 maj 2009, kl 10.15 i sal F3, Lindstedtsvägen 26, KTH, Stockholm.

TRITA-AVE -2009:19
ISSN 1651-7660

Abstract

Wind turbines are an environmentally friendly and sustainable power source. Unfortunately, the noise impact can cause deteriorated living conditions for nearby residents. The audibility of wind turbine sound is influenced by ambient sound.

This thesis deals with some aspects of noise from wind turbines. Ambient sounds influence the audibility of wind turbine noise. Models for assessing two commonly occurring natural ambient sounds namely vegetation sound and sound from breaking waves are presented in paper A and B. A sound propagation algorithm has been compared to long range measurements of sound propagation in paper C. Psycho-acoustic tests evaluating the threshold and partial loudness of wind turbine noise when mixed with natural ambient sounds have been performed. These are accounted for in paper D.

The main scientific contributions are the following.

Paper A: A semi-empiric prediction model for vegetation sound is proposed. This model uses up-to-date simulations of wind profiles and turbulent wind fields to estimate sound from vegetation. The fluctuations due to turbulence are satisfactory estimated by the model. Predictions of vegetation sound also show good agreement to measured spectra.

Paper B: A set of measurements of air-borne sound from breaking waves are reported. From these measurements a prediction method of sound from breaking waves is proposed. Third octave spectra from breaking waves are shown to depend on breaker type. Satisfactory agreement between predictions and measurements has been achieved.

Paper C: Long range sound propagation over a sea surface was investigated. Measurements of sound transmission were coordinated with local meteorological measurements. A sound propagation algorithm has been compared to the measured sound transmission. Satisfactory agreement between measurements and predictions were achieved when turbulence were taken into consideration in the computations.

Paper D: The paper investigates the interaction between wind turbine noise and natural ambient noise. Two loudness models overestimate the masking from two psycho-acoustic tests. The wind turbine noise is completely concealed when the ambient sound level (A-weighed) is around 10 dB higher than the wind turbine noise level. Wind turbine noise and ambient noise were presented simultaneously at the same A-weighed sound level. The subjects then perceived the loudness of the wind turbine noise as 5 dB lower than if heard alone.

Keywords: Wind turbine noise, masking, ambient noise, long range sound propagation

Sammanfattning

Vindkraft är en miljövänlig och förnyelsebar energikälla. Tyvärr orsakar verken bullerstörningar som kan leda till försämrade levnadsvillkor för närboende. Hur mycket ett vindkraftverk hörs beror på i vilken ljudmiljö de är placerade.

Denna avhandling berör ett par aspekter av ljud från vindkraftverk. Bakgrundsljud påverkar hur mycket vindkraftverk hörs. Modeller för att skatta två vanliga typer av naturliga bakgrundsljud, de från vegetation och från brytande vågor som presenteras i artikel A respektive B. En metod för att beräkna ljudutbredning på långa avstånd över vatten har jämförts med mätningar i artikel C. Psyko-akustiska test som utvärderade hörtröskeln och den partiella hörstyrkan av två olika vindkraftsljud när de blandas med naturliga bakgrundsljud presenteras i artikel D.

De viktigaste vetenskapliga bidragen är följande:

Artikel A: En semi-empirisk modell för att prediktera ljud från vindkraftverk läggs fram. Modellen använder moderna simuleringar av vindprofiler för att utvärdera ljud från vegetation. Ljudets fluktuationer inducerade av vindturbulens utvärderas och visar sig estimeras med tillfredställande noggrannhet. Prediktioner av vegetationsljud visar god överensstämmelse med uppmätta spektra.

Artikel B: Mätningar av ljud från brytande havsvågor och en metod för att prediktera denna ljudkälla presenteras i denna artikel. Tersbandsspektrum från brytande vågor beror på typen av brytande våg. Tillfredställande överensstämmelse mellan prediktioner och mätningar redovisas i artikeln.

Artikel C: Ljudutbredning över en havsyta utvärderas i denna artikel. Mätningar av ljudtransmission utfördes samtidigt med meteorologiska mätningar vid mottagarpunkten. Beräkningar av ljudutbredning jämfördes med mätningarna. Tillfredställande överensstämmelse mellan mätningar och modellprediktioner observerades när vindturbulensen inkluderades i beräkningarna.

Artikel D: Växelverkan mellan vindkraftsbuller och naturligt bakgrundsljud undersöktes i denna artikel. Två modeller för att beräkna ljudstyrka överestimerar maskeringen i två olika test. Vindkraftsljudet är fullständigt ohörbart vid A-vägda ljudnivåer cirka 10 dB under bakgrundsljudets nivå. Om vindkraftsbullret och bakgrundsljudet har samma A-vägda ljudnivå uppfattas vindkraftsbullret som 5 dB lägre än när det hörs ensamt.

Nyckelord: Vindkraftsbuller, maskering, naturligt bakgrundsljud, ljudutbredning på långa avstånd

Doctoral thesis

This doctoral thesis consists of a summary and the appended papers listed below referred to as Paper A, Paper B, Paper C and Paper D

Paper A K. Bolin 2009: "'Prediction method for wind-induced vegetation noise"', Accepted for publication in *Acustica united with Acta Acustica*

Paper B K. Bolin, M. Åbom 2009: "'Air-borne sound generated by sea waves"' Submitted for publication in *Journal of Acoustical Society of America*

Paper C K. Bolin, M. Boué and I. Karasalo 2009: "'Long range sound propagation over a sea surface"', Submitted for publication in *Journal of Acoustical Society of America*

Paper D K. Bolin, M. Nilsson and S. Khan 2009: "'The potential of natural sounds to mask wind turbine noise"', Submitted for publication in *Acustica united with Acta Acustica*

Division of work between the authors:

The author of this thesis has been main responsible for all four papers.

In **paper B** the theoretical and half of the measurements presented in the article was performed by K. Bolin under the supervision of Prof. M. Åbom.

In **paper C** the propagation code was written by K. Bolin under the supervision of I. Karasalo. K. Bolin also took a minor part in the performed measurements at the Kalmar straights by operating the sound sources.

In **paper D** the theoretical and experimental work presented in the article was performed by K. Bolin under the supervision of Dr. M. Nilsson and Dr. S. Khan. All authors contributed to the writing of the article.

Contents

1 Introduction

Wind energy is an environmentally friendly, sustainable energy source. In some ways they are today's Gothic cathedrals. The heights of wind turbines have now succeeded their medieval counterparts. Wind turbines also symbolize the hopes of a brighter future and solutions to serious problems as cathedrals did in the Middle Ages.Our fear has shifted from the plague to climate change but our anxiety that the end of the world is near seems to persist. Wind power will probably play a significant role in the transition to renewable energy and the global ambitions to decrease greenhouse gases. The public opinion of wind turbines is generally positive. Indeed, it is the energy source that Sweden should commit most to according to opinion polls [1] seen in Fig. 1. The support for wind energy is compact in cities as well as in the countryside. However, these positive attitudes are often shifted when wind turbine plants are planned and built close to one's home. This is commonly referred to as the "'not in my back yard"' problem. Action groups are frequently formed by local residents opposing the wind power development. The usual worries from the residents are the visual impact and the noise disturbance caused by wind turbines. The acceptance to wind power is somewhat depending on the course of action from the wind contractors. Early information and contact with nearby residents have been shown to be of large significance. However, guidelines are naturally necessary to safeguard public interest and restrict the environmental impact from wind turbines.

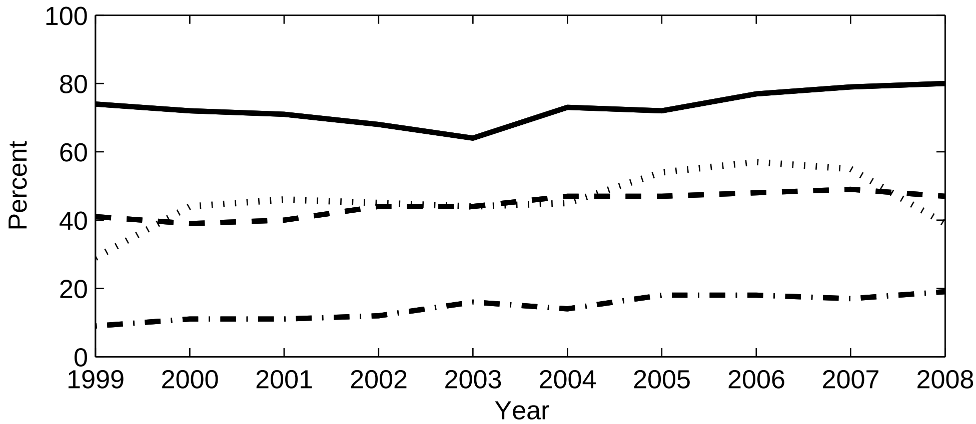

Figure 1: Opinion poll of which energy sources that should be promoted within the next 5-10 years [1]. The solid (—) line shows wind power, (- - -) hydro power, (· · ·) bio fuels and (-·-) nuclear power.

Wind turbines have grown rapidly in both number and sizes. The highest hub heights have increased from 25 m to almost 200 m in twenty-five years [2, 3]. The produced power has also increased from 50 kW to 5 MW in the same period.

This development has led to that wind power can play a significant role in the transition to renewable power sources. Some countries have come a long way. For example, Denmark produces over 20% of its electrical power from wind energy. The question where to place wind turbines are influenced by several factors which are often contradictory. For instance, access to existing infrastructure that facilitates the building and maintenance often means that the area is densely populated. Optimal locations would be regions with ample wind resources and lowest possible impact on nearby residents or temporary dwellers in recreational areas.

The global wind power will grow in the forthcoming years as signing states of the Kyoto protocol needs to fulfill their obligations to decrease greenhouse gases. This expansion will probably be particularly rapid in forests and at offshore locations. The increased wind turbine height has resulted in better conditions for wind turbines in forests. This is because the winds high above the canopies are less disturbed by the trees than close to the tops. Until now, most of the wind turbines are land based. However, large offshore farms are under construction or planned all over the world. These will exploit the vast wind resources available in this environment. By 2020 50 GW of installed offshore capacity is planned in Europe [4]. This development will lead to noise pollution along coasts and inside forests, regions invaluable for recreational purposes for large populations. These regions are often previously unaffected by community noise. Inhabitants in rural areas can be divided into those living there for economical reasons, for example farmers, and people expecting quiet and peace, for instance recreational residents. It has been shown that the former group is less sensitive to wind turbine noise than the latter group [5]. The guidelines of wind turbine noise in these areas have to be balanced between two main objectives. Firstly, the soundscape should not be highly deteriorated. Secondly, the wind turbines should be allowed produce as much power as possible.

Natural sounds have, since the beginning of our time, been a part of the ambient sounds surrounding us humans. In rural areas the sounds from wind flowing through vegetation would been the dominating sound source. This would sometimes have been interrupted by human noise from craftsmen, barking dogs or bellowing cows. In coastal regions these sounds were accompanied by the sounds from waves breaking at the shorelines. These benign soundscapes, constant for thousands of years, with the highest loudness produced by thunder or other rare natural phenomena have since the beginning of the industrial revolution gradually become polluted by new artificial sound sources. The largest upheaval from the old rural soundscape came with the automobile, today a main noise polluter in Sweden [6] and in large parts of the world. This source has seriously altered the environment in many rural areas and further deteriorations are indeed undesired.

To determine the noise annoyance it is of vital importance to investigate in which context the noise acts. Especially in the case of noise sources with low sound levels as the annoyance will be affected by the ambient sound. The work presented in this thesis tries to determine how natural background sounds influence the perception of wind turbine noise. Also, models of two common ambient sound sources are presented. Furthermore, a method to predict sound propagation at long distances has been compared to measurements of sound transmission losses over a sea surface. Hopefully, the findings in this thesis can contribute to better knowledge of the perception of wind turbine noise when it interacts with ambient sound. It is argued that guidelines of wind turbine levels should be determined by the prevailing natural background sound level. These regulations would better correspond to the perceived loudness of the wind turbines than imposing the same levels at every site. For example, in silent backgrounds the wind turbine noise levels should be severely restricted whereas at noisy conditions higher wind turbine sound levels should be allowed. Thereby, an optimization of the power output is achieved without deteriorating the soundscape. Such a procedure would also have the effect that less wind turbines have to be built to produce the same amount of power. This would be beneficial to the nearby residents by imposing less visual impact and at the same time save investment costs for the contractors.

2 Objective of the work

The aim of the present thesis is mainly threefold. Firstly, to develop tools to predict natural ambient sound sources. These could enable fast, all year assessments of the sound environments in rural and recreational areas. Secondly, to investigate if a sound propagation algorithm could be used to reproduce measurements of long distance sound transmission. Thirdly, the ability of natural ambient sounds to mask wind turbine noise has been investigated.

The question if it is necessary to measure ambient noise or if predictions could replace such measurements is discussed in this thesis. Apparently, predictions give results after a few minutes of computations while measurements are far more time consuming. This thesis identifies two main natural sound sources in rural areas. The first is sound from vegetation and the second is sound from breaking waves. The wind induces noise into vegetation. Thereby, the accuracy of this model should be depending on the correct estimation of wind speeds in the canopies. Due to this reason more elaborate models than used in earlier predictions [7, 8] of vegetation noise should be incorporated into the model. Apart from being able to take different meteorological conditions into account wind turbulence should also be included in the model. The turbulence is important as it produce fluctuations of vegetation noise. Thereby, the wind turbine might be audible at some instances even though it is inaudible at most of the time. Except for the obvious differences between leafed and leafless trees seasonal variations of for example ground conditions and meteorological conditions might occur. The aim is to construct a model of vegetation noise capable of dealing with these characteristics and to evaluate if it is accurate enough to replace in situ measurements. Air-borne sound from breaking waves could mask wind turbine noise in coastal regions. Therefore, it is the objective of this thesis to investigate this sound source. The goals of the study have been to measure and analyze the air-borne sound from breaking waves at different wave heights and at different shore types and to create a model of this sound source.

A reasonably reliable picture of the ambient noise levels at a specific site requires long-time measurements at different seasons. This would, needless to say, be both time consuming and costly. Furthermore, the ability of measurements to repress the influence from other community noise sources is questionable. Because of these reasons predictions should both save time and costs compared to measurements of ambient noise. However, the reliability of the models should be examined. In Paper A and Paper B such studies have been performed.

Long distance sound propagation is also of interest to the wind turbine noise issue. This is because wind turbines are normally placed at distances over 0.5 km from nearby residential buildings. Even longer ranges can be expected to offshore wind farms. An initial assumption would probably be that wind turbine noise should not be a problem at distances above a few kilometers. However, this is not always the case. The reason for that is mainly twofold. Firstly, wind turbines at offshore locations are almost always situated in wind farms. This is because it is relatively expensive to build and maintain in operation. The collection of turbines result in higher noise levels than stand-alone units. Secondly, the water surface acts as a reflector of sound waves and therefore the sound close to the surface is less attenuated than for soft ground. At even longer distances meteorological conditions have large influence on the sound transmission. Local wind maxima at a few hundred meters height might refract the sound downwards and trap the sound in a canal near the ground. In paper C measurements of sound transmission in the Kalmar straight are compared to simulation results.

The third objective of this thesis was to evaluate how ambient sounds influence the perception of wind turbine noise. The analysis is restricted to natural ambient sounds. This is because other community noise sources, such as traffic and air-planes, might add to the annoyance instead of positive sounds that could decrease the annoyance. This research could hopefully result in suggesting guidelines for wind turbine noise defined in terms of threshold levels or partial loudness instead of absolute values. It is believed that the results from this part could be used by noise control engineers and soundscape designers to plan how positive sound sources can contribute to better soundscapes.

3 Wind turbine noise

The first recorded attempt to harvest wind energy dates back to the 10th century when the Persians built vertical axes windmills. In the Middle Age horizontal axes windmills were used in Europe. These mills were not only used to grind but also for pumping, sawing and other mechanical labor. Until the Industrial Age wind mills were an important part of the energy production. During the Industrial Age coal and later oil became the dominant power sources. The wind generation of electricity started in the late 19th century. These wind turbines were used at farms and in other small communities. As these locations were connected to central power grids the need for electrical self sufficiency diminished.

In the 1960s an increased environmental awareness set off in the western world. The environmental consequences of fossil fuels were started to be shown. Nuclear power was also discredited by the fear of nuclear accidents and by the Harrisburg incident. It was in the light of this background that development of modern wind turbines began. The earliest major commercial wind turbine development was sited in California following the Oil Crisis in the mid 1970s. However, the oil prices dropped in the subsequent decade and the wind power rush in California ended. In the 1990s the development of wind turbines were focused to Denmark and Germany. The turbine sizes were steadily increased and the reliability was improved. The average wind turbine power output has increased forty times during the last 25 years. Today the highest wind turbines are 180 m and has a blade radius of 60 m [3].

In the 1980s the first articles regarding noise annoyance from large wind turbines were published by Manning [9] and Hubbard et al. [10]. Much research has been conducted since these papers to arrive at the present knowledge regarding wind turbine annoyance. In the early stages mechanical noise sources dominated. But improved sound isolation, e.g., rubber coated teeth in gearboxes and sound isolation of the nacelle have resulted in that today noise is mainly caused by broad band aerodynamic sound from the blades. This source produce a distinct "swooshing" a sound somewhat similar to distant aircraft noise.

Different noise emission regulations for wind turbines exist in Europe. Three basic strategies are the German, Dutch and British which are described below. The German noise standard [11] allows for a sound level of 45 dB. This simple procedure will almost certainly result in suboptimal power output especially at higher wind speeds. This is because the ambient noise level usually increase faster than the turbine noise, thereby increasing the masking probability [12]. The Dutch noise regulation [13] adjust the allowed turbine limits depending on the wind speed. Thereby, it implicitly accounts for the masking by background sound. This result in a simple but coarse procedure as these standardized ambient sound levels should be set low to avoid annoyance. The assumption that ambient sound levels are approximately the same in different locations could be valid in a homogeneous landscape like the Dutch farmland but many other countries have larger deviations in the rural landscape resulting in large variations of natural sounds in different locations. This would result in very tight noise emission limits and non-optimal output from wind turbines. Thereby, increasing the number of wind turbines to produce the same amount of electricity. The British assessment method [14] allows for 5 dB higher turbine sound level L_{Aeq} than the measured background sound levels $L_{A,90}$ at different wind speeds. This procedure will hopefully result in optimized power output without causing large disturbances at nearby dwellings. However, extensive measurements for all seasons have to be performed at every wind turbine project and hence this method can prove both time-consuming and expensive. These three different approaches have their advantages and disadvantages respectively, either suboptimal power output or time consuming and expensive.

4 Ambient noise

To evaluate the impact of wind turbine noise knowledge of the surrounding soundscape is very important. This is partly because the allowed wind turbine noise levels are quite low and therefore seldom dominates the soundscape. Furthermore, the broadband character and less amplitude modulations exhibited by today's turbines make them easier to conceal compared to older turbines where contributions from mechanical noise sources were common and amplitude modulations often clearly audible.

4.1 Vegetation noise

The sound induced by the wind in vegetation should be an ideal masker of wind turbine noise. The reason for this is mainly twofold. First, at times with high wind speeds the wind turbine noise emission will increase [15]. These conditions will coincide with increasing sound levels from vegetation and consequently better masking possibilities. Secondly, the noise produced by both wind turbines and vegetation are of steady and broadband character.

Although daily perceived by a large part of the population a surprisingly small amount of research has been conducted in the field of sound generated from vegetation. Measurements of ambient noise levels are performed on a routine basis but only a small amount of these have explicitly investigated noise generation from trees rather than determining the sound level at particular locations. The report by Sneddon et al [16] examines the noise generation from mixed coniferous forests in a National Park in California. All year measurements of vegetation sound were performed in Denmark by Jakobsen and Pedersen [12]. The first stringent effort to model vegetation sound were conducted by Fégeant who proposed a semi-empirical prediction model of vegetation noise in Refs. [7, 8]. This method takes different tree species and vegetation geometries into account. The model was validated for cases of non-turbulent flow. Further work by Fégeant [17] stressed the importance of wind turbulence causing variations in the level of vegetation noise. However, field measurements have only been performed at wind speeds of 7 m/s and below [8, 17]. Confirmation of the theory above these conditions is considered necessary in order to predict the noise at higher wind speeds where the masking effect should increase. Furthermore, the analytical expressions in [7] are not suited to estimate sound fluctuations and complicated vegetation geometries. Therefore the semi discrete model presented in paper A in this thesis is superior, at least in these aspects. This model is coupled to a method producing time series of turbulent winds which satisfactory estimate the time fluctuations of vegetation noise.

4.2 Air-borne sea noise

The wind resources in offshore and coastal regions are abundant. Therefore, these areas have since a long time been suitable for wind energy. Offshore turbines are still expensive but the costs will probably decrease when the technical solutions matures. Europe alone has predicted a 50 GW offshore capacity by 2020 [4]. The landscapes around our coasts have an immense value for residential and recreational purposes. To deteriorate this soundscape by introducing wind turbine noise is indeed undesirable. Such attempts often produce strong public opinions against wind turbine development. The reasons for this are manifold. These areas are often previously unaffected by community noise. The residents in coastal areas do often live there to have peace and quiet and are inclined to preserve an unspoiled countryside. These people also commonly lack an economic incentive in wind power development which has been shown to have mitigating influence on the noise annoyance [18].

The dominating sound source would be breaking sea wave noise in coastal areas previously not affected by community noise. Therefore, knowledge of this sound source should be crucial when evaluating the impact of noise from offshore or coastal wind farms. Sea waves build up when the wind direction is toward land. Such winds would probably also yield less dispersed sound propagation from wind turbines. Therefore, higher levels of wind turbine noise would often coincide with higher levels of masking sea sound. This observation would contribute to the usefulness of masking wind turbine noise by sound from sea waves. For example, complaints of offshore wind turbine noise have been reported at some locations when the wind direction was from the shore. Obviously, the masking from the waves decreased. Consequently, even though the absolute sound level should be lower in upwind conditions the residents heard the noise much better. This also highlights the adverse effects of absolute levels as wind turbine noise guidelines. The residents were annoyed when the wind turbine noise level supposedly decreased.

4.3 Predictions, measurements or both?

To estimate ambient sound two alternative procedures are considered possible. The first is measurements and the second is predictions. It is suggested in the two papers (A and B) appended to this thesis that predictions are robust and has a reasonable accuracy. The decisions to use semi-empiric models are based on the complex nature of the sound sources.

The vegetation noise model is considered a reasonable approximation of the real acoustic processes within canopies. It has been observed when using the prediction method for vegetation noise that it is important to specify the input parameters with care. However, this is sometimes not enough to avoid estimation errors. It is believed that such discrepancies could arise from differences from the assumed wind profile, deviations from the properties of a standard tree or simply from incorrect estimation of the extension of the vegetation. Breaking wave sound is also a complicated physical phenomenon. It is important not only to underwater acousticians as a source of ambient sound but also to the flux of oxygen into the oceans. Because of these reasons the underwater noise and bubbles is thoroughly documented, see Ref. [19, 20, 21] among others. However, the bubbles that are most interesting for air borne sound are the large bubbles that surface rapidly after the breaking as these could act as Helmholtz resonators. Unfortunately, neither bubble sizes nor time durations of these sizes have been reported in any literature known to the author.

The insufficiencies of the two proposed models to accurately describe the physical mechanisms are unfortunate. However, it is irrelevant to their ability to estimate sound levels and spectra for these ambient sounds. To be able to quickly estimate ambient noise levels could be of major importance to faster determine the environmental impact from wind turbine noise. It could also be used as a tool in the planning process to investigate the potential of the ambient sound to mask wind turbine noise in large areas. In the case of deciduous trees these models are even more valuable as otherwise measurements would have to be performed at both leafed and leafless conditions.

It is shown in the appended papers (paper A and B) that these models are sufficiently robust and reliable to estimate the ambient sound in most circumstances. However, to estimate the vegetation noise model could be unreliable in complex landscapes where the wind profiles are difficult. An advantage compared to measuring ambient levels is that other community noise sources do not influence the prediction models. This is considered important as already noise polluted areas should not be penalized by further deteriorated environment. It is believed that prediction models could be used to estimate ambient levels when planning wind turbine establishments. It can also be used to select locations where to measure ambient noise. However, to solely rely on estimations from models might be ill advice. Sufficient validations of the models have not yet been performed and measurements are advised to verify prediction results at some locations before masking of wind turbine noise is finally evaluated. Measurements could also be used to investigate if other sound sources, for example, whitewater rafts or waterfalls influence the natural ambient sound.

5 Sound propagation

The performed research within the field of sound propagation is indeed vast. It exists numerous different methods to predict sound transmission. For example, ray tracing algorithms and normal mode solutions are frequently used. This thesis do not give a complete picture of the previous and current research within the field of sound propagation. This is because this thesis also consider other research areas. Also, the author humbly admits that his knowledge within the field of sound propagation is restricted.

However, efforts have been performed to implement a Green's function parabolic equation (GFPE)- algorithm. This has resulted in an investigation of long range sound propagation over a sea surface.

5.1 Green's function parabolic equation

The GFPE algorithm belongs to the so called the parabolic equation (PE) family. Other methods within this group is for example the Crank Nicholson PE. These methods begin by inserting a starting condition as a function of height (z-direction). This profile can either be calculated by another sound propagation algorithm or directly decided. However, the starting condition has to be chosen with care as the solution can exhibit strange behavior otherwise. The starting condition at $r = 0$ is then propagated in the horizontal direction one step to, $\Delta r + r$. This stepping is iterated until the set propagation distance is reached. The main advantage of the GFPE method is that it uses much longer horizontal steps than other PE algorithms [22]. Thereby, the computation time is significantly reduced compared to other sound propagation methods. The algorithm is derived from the Helmholtz equation in cylindrical rz coordinates. The far-field approximation of this equation after a variable substitution of the acoustic pressure, p, and r as $q = pr^{1/2}$ and the wave number $k(z) = \omega/c(z)$, which yields

$$\frac{\partial^2}{\partial r^2} q(r,z) + \frac{\partial^2}{\partial z^2} q(r,z) + k^2(z) q(r,z) = 0 \qquad (1)$$

which is a two-dimensional wave equation. By inserting the variable substitution $\phi = exp\,(-ik_0 r)q$ into Eq (1) and using alternatively the spectral theorem of functional analysis, see Gilbert and Di [22], or the Rayleigh 2nd integral, see Salomons [23], the steps of the GFPE algorithm is reached and shown in Eq. (2) and Eq. (3).

$$
\begin{aligned}
\phi(r+\Delta r, z) = & \exp\left(i\frac{\Delta r \delta k^2(z)}{2k_r}\right) \\
& \times \left[\frac{1}{2\pi}\int_{-\infty}^{\infty}(\Phi(r,k') + R(k')\Phi(r,-k')) \right. \\
& \times exp(i\Delta r(\sqrt{k_r^2 - k'^2} - k_r))e^{ik'z}dk' \\
& + 2i\beta\Phi(r,\beta) \\
& \left. \times exp(i\Delta r(\sqrt{k_r^2 - \beta^2} - k_r))e^{-i\beta z}\right]
\end{aligned} \tag{2}
$$

where k_r is a reference wave number ($k_r = k(0)$ in this paper [23]), $\delta k^2(z) = k^2(z) - k_r^2$, $R(k') = (k'Z_g - k_r)/(k'Z_g + k_r))$ is the plane-wave reflection coefficient, Z_g is the normalized ground impedance, $\beta = k_r/Z_g$ is the surface-wave pole in the reflection coefficient and $\Phi(r,k)$ is given in Eq. (3)

$$
\Phi(r,k) = \int_0^{\infty} exp(-ikz')\phi(r,z')dz' \tag{3}
$$

which combined constitute the fundamental step in the GFPE-algorithm.

The GFPE algorithm has a few more advantages, the ground conditions can be changed at each new horizontal step and turbulence can be easily included. Turbulence causes scattering of the sound. Consequently, shadow zones, due to atmospheric conditions causing upward refraction are avoided by including turbulence. The turbulence can be modeled by introducing random disturbances into the first term in Eq. (2). These random perturbations are calculated from power spectral densities capturing the characteristics of the turbulence. To resemble the spatial coherence from eddies these perturbations are gradually changed between horizontal steps.

5.2 Meteorology

Sound propagation up to around one kilometer distance from the source is mainly determined by the prevailing ground conditions. A harder acoustic surface results in less sound attenuation. However, Johansson [24] showed an increased importance of meteorological conditions at longer distances.

The atmosphere can be divided into different layers, from the boundary layer close to the ground up to the stratosphere. Concerning sound propagation the horizontal extension determines the amount of needed information to acquire accurate predictions. As a rule of thumb, the longer the propagation distance meteorological information at higher altitudes is necessary to accurately predict sound propagation. Meteorological data that influence the sound speed is temperature, pressure and humidity. From these quantities the sound speed can be calculated according to the procedure outlined in ISO9613 [25, 26]. The effective sound speed is also determined by the wind velocity which is simply added to the sound speed calculated from ISO 9613.

The meteorological conditions are mainly governed by the sun and change during the day. Here follows some main properties of the atmospheric states. At night the wind profile is often stable. Low vertical wind motions occur because the air is colder and denser close to the ground than further up. This results in a steeply increasing wind speed gradient. When the morning comes the sun warms the ground. The air close to the ground then becomes less dense than the air above. Then the mixing of air increases and an unstable atmosphere can be observed. This mixing of air results in less vertical variations of wind speed than at stable conditions. Differences naturally occur from these normal conditions due to meteorological and geographic reasons.

Increasing wind speed with height is the normal condition in the atmosphere. This is due to the decreased resistance from the ground with increased height. However, sometimes the wind speed exhibits maxima at a few hundred meters height. These conditions are called low level jets and were observed by Balckadar [27]. At long distance sound propagation it has been shown that low level jets refract the sound downwards [24]. Thereby, the sound is trapped in a canal between the ground and the jet height. At such occasions the geometrical spreading was shown to be cylindrical instead of spherical [24] as would have been the case if the sound was not confined within the canal.

6 Combination of sounds

The auditory process is indeed a complex system. It is normally divided into two parts. The first part is the peripheral system ranging from the outer ear via the eardrum to the cochlea. The sound starts to propagate through the earlobe which acts as an antenna and allows the auditory system to estimate the direction of the incoming sound. After the sound has moved through the external auditory canal it reaches the eardrum which is connected to a bone called the hammer. Via two other bones (the anvil and the stirrup) the vibrations of the eardrum is transmitted to the cochlea through the oval window that separates the air filled outer and middle ear and the liquid filled inner ear. When the sound pressure reaches the cochlea movements of the hair cells transform the fluctuations into nerve impulses. The second part is called the central auditory system. The nerve impulses propagate through the cochlear nerve into the brain and eventually reach the cortex where the nerve impulses are transformed into sensations. This sophisticated system allows us to perceive silent whispers and is robust enough to withstand noise from a starting aircraft, i. e. sound pressures that differ around 10^6 times in magnitude. In the neurological part the auditory system can also distinguish between music, noise and speech. Therefore, hearing is indeed a remarkable and advanced sensory organ.

Noise is usually defined as unwanted sound. Consequently, what some persons perceive as noise is to other music or desired sound. The proportion of parents perceiving their teenagers music as noise is probably quite high. Regarding wind turbine noise it has been shown that economical incentive influence the perceived annoyance [18]. The wind turbine owner regards it as wind turbine sound while his or her neighbors regards it as noise. The opinion of wind turbine sound could therefore be considered a central issue that directly influences the perceived annoyance. Apart from the attitude, the interaction between wanted and unwanted sound could influence the perception. It is therefore considered interesting to examine interaction effects between wind turbine noise and ambient sound.

Combinations between different sounds in the auditory system are occurring all the time. The question of how these interact is even more complicated than how they are individually perceived. How to distinguish between different sounds is mainly determined in the central auditory system. When sounds are combined the perception of them are influenced by each other. Loudness interaction effects between two sounds could be threefold; the first is that they amplify each other which is called loudness summation. Thereby, the loudness of one sound is perceived louder than if heard alone. This could occur if two sounds have a similar character. For example, it has been shown that combined traffic noises are perceived louder than if heard separately [28]. The second alternative is that the sounds are not influenced by each other. This might occur when two distinctively different sounds interact. For instance, the differences might be in character, directivity, frequencies or temporal. For example, broadband noise and tonal sounds are often easily separable and might therefore not interact with each other. The third possibility is that they will mask each other. This is the opposite of loudness summation. In this case a sound is perceived less loud if are heard together with the other sound. For instance, the speech intelligibility is reduced close to a busy street compared to a quiet countryside. Masking can be separated into two different regions. The first is absolute masking when one sound is inaudible. This could mainly occur when the frequency contents of the two sounds are similar and the loudness difference is large. The second alternative is called partial masking when both sounds are audible, but the loudness of a sound is lower than if heard alone. Which of these three interactions, loudness summation, no interaction or masking that occur for different combinations of sound is difficult to predict. Therefore, the interaction between wind turbine noise and ambient sound might evoke different reactions. If ambient sound increase the perceived wind turbine loudness then stricter guidelines would be necessary than if the turbine noise is heard alone. On the other hand, if masking occurs raising the allowed noise emission would be possible.

The audibility of wind turbine noise is highly dependent upon the ambient sound. The reason for this is mainly twofold; the first is that wind turbine noise has low sound levels. This makes the perception of wind turbine noise susceptible to other sounds. Louder noise sources could dominate the soundscape while wind turbine noise easier could disappear in other sounds. The second reason is that the wind turbine noise is of relatively steady and broadband character. The steadiness and absence of tonal components yields sound that is probably difficult to distinguish from broadband ambient sounds.

Total masking is not a binary process with guaranteed audibility or inaudibility at a certain level. Intraindividual variations as well as fluctuations of responses from the same person occur. Therefore, auditory system is to sophisticated to be described by a simple totally deterministic model. Especially the neurological part of the process is difficult to estimate. However, it is clear that the perception of sounds is determined by stimuli as well as a decision making process. The same stimuli might provoke different reactions at different times. Psycho-physicist showed in the 1950s that the response was depending on the test procedure [29]. For example, the reaction of the subjects depended on how often the stimuli occur and the reward of a hit contra the penalty of a miss or a false alarm. These observations resulted in that the signal detection theory were proposed by Green and Swets [29]. This theory attempts to describe the response bias and to create unbiased quantities.

When vegetation noise mask wind turbine sound were estimated by Fégeant [30]. This investigation was done by calculating the detectivity index. However, the obvious similarities between the broadband noise of vegetation and wind turbine sound could cause informational masking [31]. This makes it interesting to apply psycho-acoustic models of energetic masking [32, 33] to investigate if these are accurate. Therefore, a laboratory study has been performed in paper D to investigate the masking threshold and partial loudness of mixed ambient sound and wind turbine noise. Apart from the vegetation sound the masking potential of sea wave sound has also been studied, this is considered important due to the large wind farms planned in offshore locations all over Europe and since sea noise commonly dominate the coastal soundscape.

6.1 Energetical masking

The first effort to produce a stringent description of loudness was presented by Fletcher in the nineteenth century [34]. A straightforward axiom regarding masking is that the sound that is masking the signal has to be louder at all audible frequencies to guarantee total masking. This assumption leads to so called energetic masking. The development of modern psycho-physic test procedures and computers allowed Zwicker to develop modern loudness models [35]. In recent years the concepts of Zwicker's loudness model has been improved by researchers at the Cambridge University. These advances has been spearheaded by Moore and Glasberg [32, 33] which has resulted in loudness models for both steady and time-varying sounds. The basic concepts of these models are that the sound is filtered through the outer and middle ear and transformed into a frequency response function at the cochlea. These response functions are then assumed proportional to the hearing sensation.

6.2 Informational masking

The assumption of energetic masking models that is the masker has to be louder than the signal at all audible frequencies was proven inaccurate by Carhart in the late 1960s [36, 37]. He observed that when speech was masked by other speech the signals were more difficult to detect than expected from models of energetic masking. That is, the masking thresholds were significantly higher than predicted. He concluded that the similarity between the signal and masker affected the threshold. Another effect that has been shown to increase the masking threshold is the trial-to-trial stimulus uncertainty [38]. The results from these studies show that masking could not solely be estimated by energetic masking models. Due to these limitations the theory of informational masking has been attracting attention from several researchers in recent years [39, 40, 41].

The influence of informational masking on the masking of wind turbine noise could thus be twofold. The first observation is that natural ambient sound and wind turbine noise share a common broadband character. The sounds also show reasonable spectral overlapping. Therefore, it is suspected that the similarity between these sounds might contribute to informational masking. The reason for this is because the hearing system might have difficulties to distinguish between the sounds. The other trial-to-trial uncertainty component of informational masking could be adjusted by the information given in psycho-physic tests. This uncertainty part has deliberately been chosen low in the tests in paper D. This is because it is assumed that residents near wind turbine sites would recognize the wind turbine noise and therefore show low amounts of uncertainty in detecting the noise.

6.3 Loudness and annoyance

The coherence between loudness and annoyance of noise can usually be assumed high. That is, the louder a sound is perceived the more annoyance it will cause. However, at low sound levels the correlation between loudness and sensory pleasantness is low [35]. It is even suggested that loudness below that of conversation between two people in quiet do not influence the sensory pleasantness (p. 245 in [35]). Other properties, e.g. sharpness and roughness, of the noise determine the pleasantness of the noise at low sound levels. Presumably, lower pleasantness of a noise would correlate to higher annoyance. Perceived annoyance of wind turbine noise is depending on other factors than loudness. This have been verified by Persson Waye et. al. [42]. In this report it was shown that the annoyance was different from various wind turbines at constant A-weighed sound levels of 40 dB. Furthermore, it has been showed by Brown and Muhar [43] that by introducing "positive sounds" in the soundscape annoyance can be decreased. These results both suggest that A-weighed sound levels might not be the most precise measure to assess annoyance from wind turbines.

7 Summary of papers

This section accounts for the most important methods, results and conclusions in the appended papers. The first two papers (A and B) concern natural ambient noise. Measurements and models predicting ambient sounds are presented. Paper A investigates sound from vegetation while paper B concern sound from breaking waves. The third paper (C) examines sound propagation over a sea surface. Measurements performed in the Kalmar straight are compared to calculations by a suitable sound propagation model. In the fourth paper (D) the influence of interaction between wind turbine noise and three natural ambient sounds is studied. Total and partial masking tests are compared to predictions from two existing loudness models.

7.1 Paper A- Prediction method for wind-induced vegetation noise

In the 1970s a normal hub height of wind turbines was around 25 m. These machines were inappropriate to place in forested areas. This is because the wind conditions at this height are deteriorated because of the flow resistance from the trees. Today normal hub heights are between 80-120 m. With a blade radius of 50 m this means that the wind energy is harvested up to 170 m height. At these altitudes the deteriorated wind conditions in forests are much less than close to the canopies [44]. Therefore, the opportunities to place wind turbines in forested areas are today significantly improved. In many ways forests can be considered suitable for wind energy development. From the contractor's and landowner's point of view forestry can continue. Forests are usually less densely populated than open areas and therefore less public reactions could be expected. For those living nearby the plants will be better concealed than in open landscapes. This has been shown to decrease the probability of noise annoyance [5, 18]. The vegetation can also mask vegetation noise by introducing a "positive" sound source to counterbalance the noise annoyance [43]. Due to these reasons the nuisance by wind turbines can be suspected to be less in forested areas compared to in open landscapes. Therefore, guidelines could be different in different regions.

The potential of vegetation sound to mask wind turbine noise can be expected to be quite good. This is because both sounds are of broadband character and vegetation sound as well as wind turbine noise increase with wind speed. As seen in Fig. 2 the spectral resemblance between vegetation sound and wind turbine noise suggest that masking is possible. To determine the vegetation sound either site specific measurements [12] or prediction models [7, 8] could be used. The main advantages to use predictions are that they are faster and less costly than measurements. Therefore, the aim of this paper has been to improve the vegetation noise model presented by Fégeant [7, 8]. This work has followed two main directions. Firstly, to validate the proposed vegetation noise models at higher wind speeds than has earlier been reported. Secondly, to improve the model by including accurate wind profiles, turbulent wind fields and an acoustic model of leafless trees. The first objective has been accomplished and measurements with wind speeds up to 8.5 m/s are reported as can be seen in Fig. 3. The second objective was to improve the prediction accuracy compared to the Fégeant model. Efforts have also been taken to model leafless deciduous trees and incorporate wind field simulations into the model. These improvements seem to give satisfactory estimations of sound emission from leafless trees as well as reasonable estimations of the time fluctuations generated by wind turbulence.

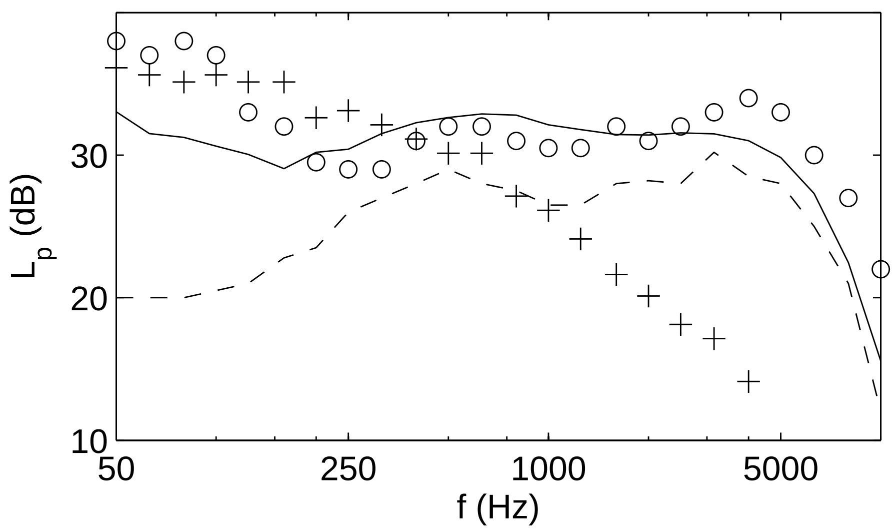

Figure 2: Showing measurements and simulations from noise from an edge of aspens and wind turbine noise. Sound pressure level in third octave bands at U=4.4 m/s. (∘) measurement, (—) prediction by Bolin, (- - -) prediction by Fégeant and a spectrum from a 2MW wind turbine (+).

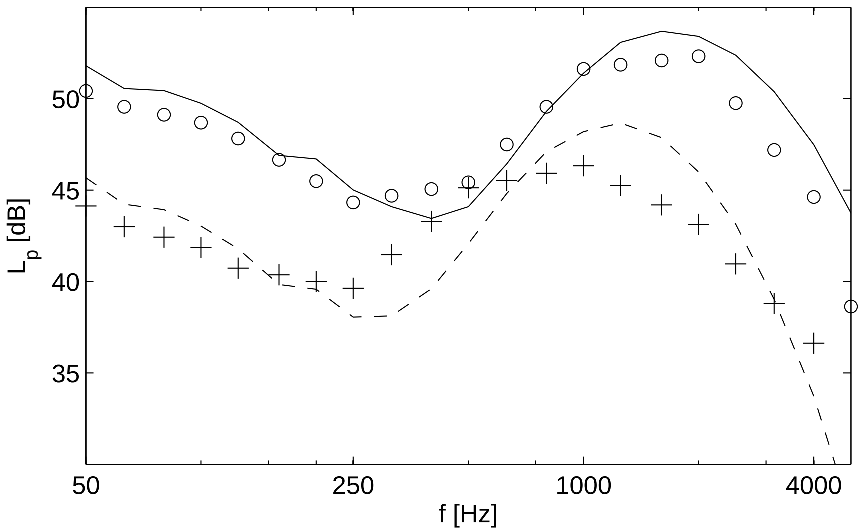

Figure 3: Third octave band spectrum of sound pressure levels. Site 1 in Paper A is shown. The wind speeds are 8.5 m/s for (○) measurement and (—) simulation. U=6.1 m/s (+) measurement and (- - -) simulation.

7.2 Paper B- Air-borne sound generated by sea waves

When the amphibians climbed up on land the sound they would have heard is that from breaking waves. Thus, quite many generations prior to us have heard the swell. This sound can often dominate the soundscape in coastal regions. Waves build up at inland wind directions. These conditions should often concur with downwind conditions from offshore wind turbines. In these conditions the sound is expected to be less dispersed as shown in Paper C. Therefore, higher noise levels from offshore turbines should often coincide with increased levels of masking sea wave sound. Today's pitch regulated wind turbines also allow for active noise emission control. Consequently, wind turbine noise could be adjusted to prevailing ambient conditions to avoid nuisance to nearby residents. Masking of offshore and coastal wind farms is of increasing importance as these regions hold huge wind resources. Within the year 2020 it is predicted that the installed wind power at offshore locations should be 50 GW [4] in Europe alone. This energy is equivalent to that produced in around 50 nuclear reactors. To optimize the produced power from these turbines is consequently very important. One step toward such regulation would be to determine the noise imission with respect to the prevailing ambient sound. To facilitate such a procedure a model describing the sound from breaking waves could be used to estimate the ambient sound in coastal regions.

To estimate the masking effect from waves proper knowledge of breaking wave

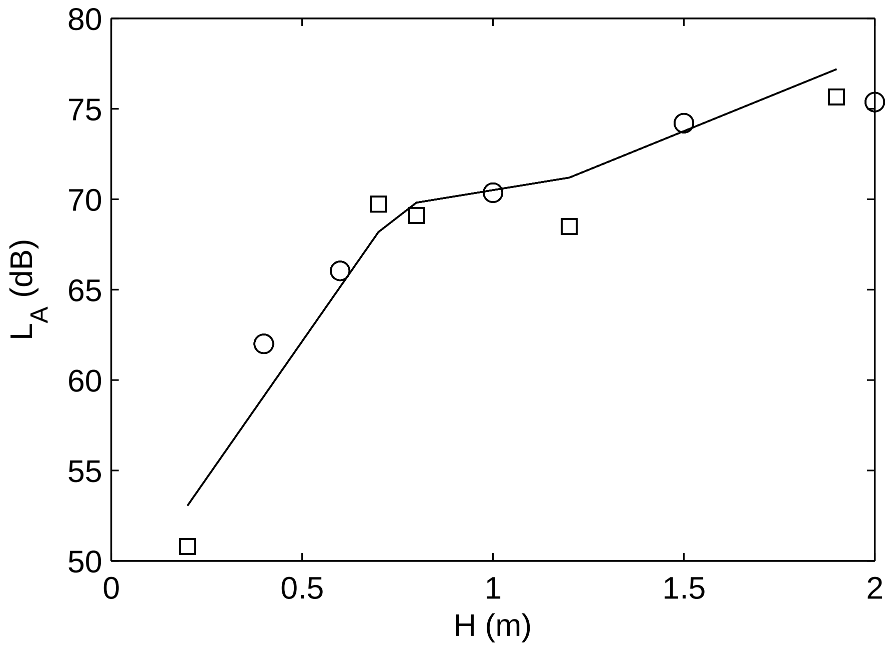

Figure 4: A-weighed sound levels as a function of wave height. The circles (∘) represent measurement used to estimate model parameters. The squares () represent measurement from sites not used for parameter estimations. The line (—) is the model prediction.

noise is necessary. Paper B shows measurements and derives a semi-empiric model of breaking wave noise. The physical origin of breaking wave noise is discussed. As can be seen in Fig. 4 the sound levels from breaking waves mainly depend on the wave height. However, the spectra changes if the wave is spilling or plunging. This can be seen in Fig. 5 where the energy is shifted toward lower frequencies in plunging waves. The energy of the spectra is shifted toward lower frequencies when waves change from spilling to plunging.

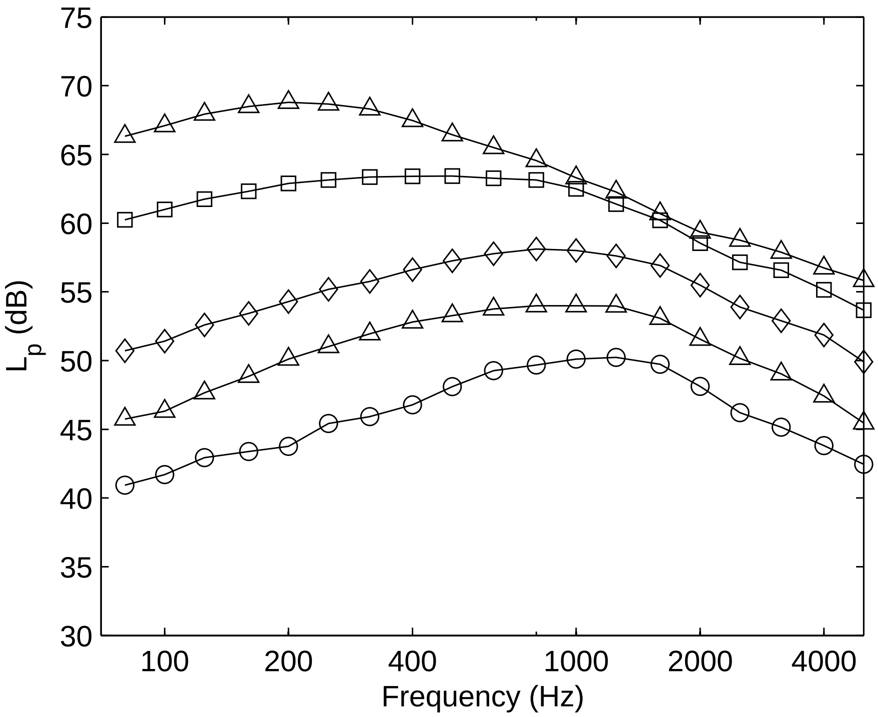

Figure 5: Third octave band spectrum from measurement. Significant wave heights for spilling waves were 0.4 m (○), 0.6 m () and 1.0 m (◇) and for plunging waves 1.5 m () and 2.0 m (△).

The conclusions from Paper B are that satisfactory agreement between the proposed model and the measurements is observed. Regarding the physical origins of air-borne sound from breaking waves there seems to be several possible explanations. One is that underwater bubble oscillations transmit sound to the air. Another possible explanation is that bubbles cracking at the surface act as Helmholtz resonators.

7.3 Paper C- Long range sound propagation over a sea surface

Long range sound propagation over water surfaces can be considered important as large offshore wind farms are planned all over the world. These will exploit the vast wind resources available in this environment. Offshore wind turbines are often situated in shallow waters near a coast due to cost increases with increasing water depth. Such installations have given rise to concerns for noise disturbances in adjacent coastal regions. The areas are often priorly unaffected by community noise and used for recreational purposes. Since atmospheric sound propagation is highly dependent upon the prevailing meteorological conditions, the level of such noise disturbances vary significantly with time.

Computer software of the GFPE algorithm has been constructed in MATLAB. The results from this code show perfect agreement to the reference cases reported in the paper from Gilbert and Di [22]. The model inserts an artificial absorption layer at the top to suppress spurious reflections. The vertical step size is 0.1 λ while the horizontal step size is chosen to 10λ. Ground impedances are different at the sea and at land. This changing ground conditions has been implemented in the code. At the ground there were pebbles and gravel at the shore followed by pasture land up to the receiver position. The ground conditions of the sea have distinctively different properties than at land. A calm sea is almost totally reflective. Waves should influence the reflection by introducing scattering of the sound waves.

Measurements were conducted between the 15th and the 21st of June 2005 in the Kalmar strait and the island Öland in the Baltic Sea. The measurement setup can be viewed in Fig. 6.

The measurements were performed in the summer because most annoyance from wind turbine noise could be expected in this season. Also, low level jets are a frequently occurring meteorological condition at that time of the year. These conditions are characterized by a local wind speed maximum at low levels (below approximately 1 km [45]). If the direction of the jet is downwind toward the receiver a local wind velocity maximum in the wind speed profile could occur. Under these circumstances the sound might be refracted downwards as can be seen in Fig. 7. The maximum wind speed occurs at approximately 0.2 km and the sound is clearly trapped within the surface and this height. This results in transmission losses less than 80 dB at the reception point. Consequently, cylindrical spreading of the sound could be expected in these conditions, as showed in [24], instead of spherical spreading that is normal without a downward refractive atmosphere. Spherical spreading are shown to occur at upwind conditions. Meteorological profiles at the receiver point were measured several times during the day using radio probes and theodolite tracking of free flying balloons [45].

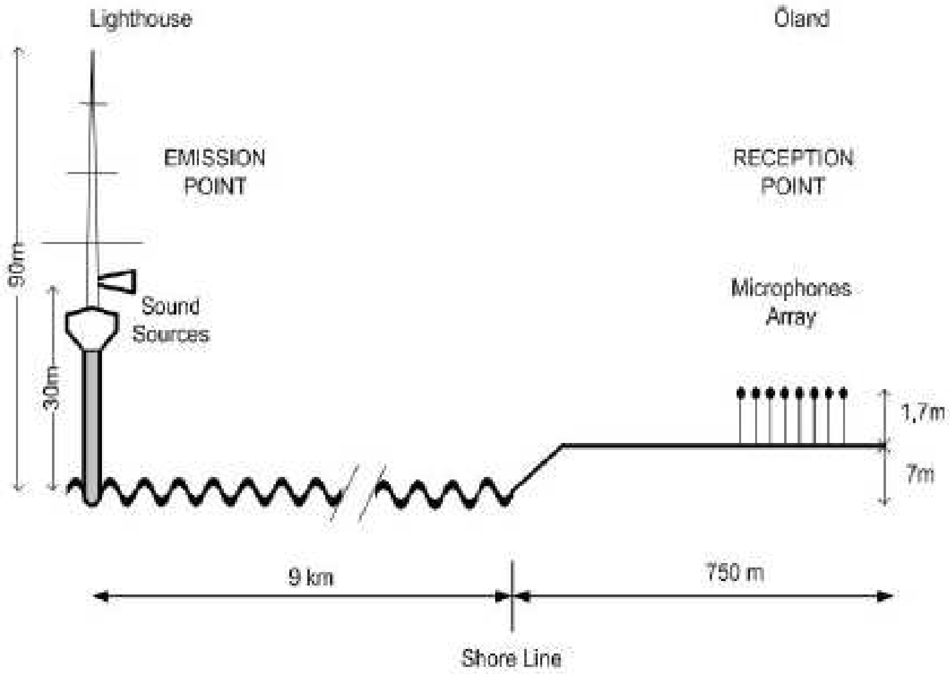

Figure 6: This figure shows the in situ setup at the emission point and reception point.

These measurements were performed by staff from the Department of Earth Sciences, Uppsala University. Wind velocity (horizontal components), humidity and temperature were measured up to 3500 m height. The reason for the need to determine the atmospheric properties at high altitudes is that these influence the sound transmission at long propagation distances.

The results support that sound propagation modeling including effects of detailed meteorological data can be used for reliable prediction of transmission loss. In particular, the predicted transmission loss remains reasonably accurate under varying meteorological conditions and follows the variations observed in the transmission loss measurements in a realistic way. The results further indicate that the sound propagation model must include effects of turbulence in the atmosphere for accurate predictions of the transmission loss into shadow zones. Fig. 8 and Fig. 9 shows the difference between the simulations of upwind conditions excluding and including turbulence. As can be seen the scattering introduced by the turbulence avoid predictions of shadow zones.

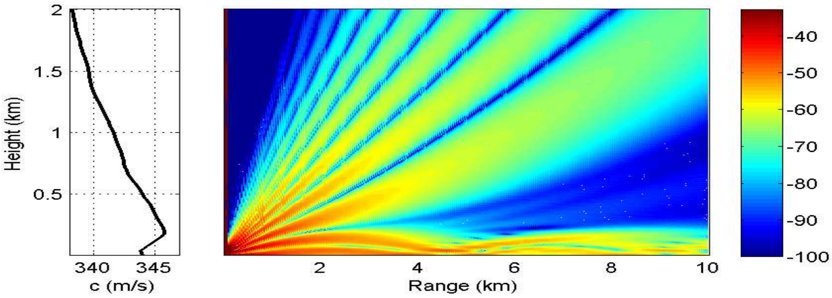

Figure 7: Simulation results for the 80 Hz case at 12 am the 16th June. The stationary wind field is included. The sound speed profile is shown to the left. Sound field is shown to the right. The sound field is the transmission loss in dB.

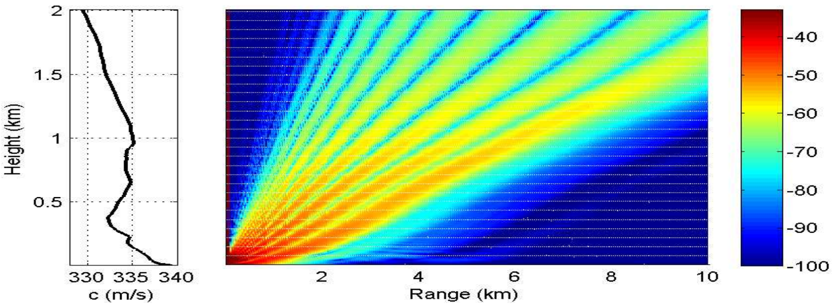

Figure 8: Simulation results for the 80 Hz case at 8 pm the 17th June. The stationary wind field is included. The sound speed profile is shown to the left. Sound field is shown to the right. The sound field is the transmission loss in dB.

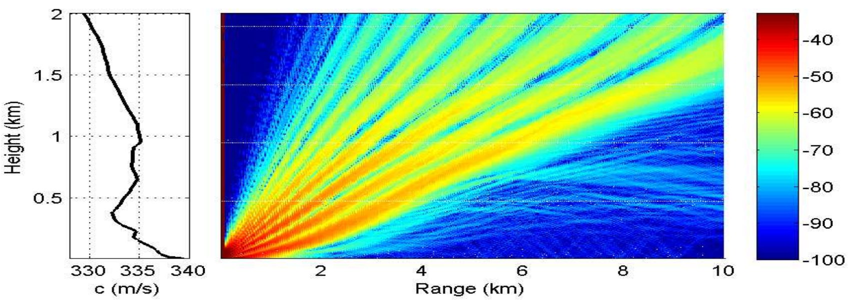

Figure 9: Simulation results for the 80 Hz case at 8 pm the 17th June. The turbulent wind field is included. The sound speed profile is shown to the left. Sound field is shown to the right. The sound field is the transmission loss in dB.

7.4 Paper D- The potential of natural sounds to mask wind turbine noise

Wind turbines are causing disturbances to nearby people, for instance, emitting noise and disrupting the view. Exposure-effect relationships show that wind turbine noise may evoke annoyance at low levels, below 45 dB L_{Aeq} [5]. The increase of wind turbines may thus be particularly problematic in quiet areas with low ambient sound levels. Natural ambient sounds are assumed dominating in such environments. Therefore, masking of wind turbine noise by these sounds should be evaluated. This could be useful for environmental impact assessments of wind turbines noise in quiet areas, or as tools for landscape architects. Existing partial loudness models, developed by Moore [32] and Glasberg and Moore [33] may be used for these purposes. However, these models have as yet not been tested in experiments with wind turbine noise. This is the first systematic listening experiment on masking of wind turbine noise by natural sound sources known by the author. The main objectives of the experiments presented in paper D were to determine detection thresholds and partial loudness of wind turbine noise in environments of natural ambient sounds.

The experimental sounds consisted of two types of wind turbine noise (single and multiple turbines) and three types of natural ambient sounds. The two wind turbine noises were distinctively different from each other. The single wind turbine noise was measured at a 100 kW turbine from 1991. This noise contained amplitude modulations at around 1 kHz. On the other hand, the multiple wind turbine noise was a recording from 17 modern 2 MW wind turbines. A low pass filter with cutoff at 1 kHz had been used on this sound to suppress unwanted high frequency components. The three natural ambient sounds were from coniferous trees, deciduous trees and sea waves. Two different experiments were conducted. The first was a forced choice method. This aimed at tracking the threshold as defined by ISO [46] as the level where subjects detect wind turbine noise at 50% of the tries. The second test was a loudness matching test. The objective was to determine how ambient sound influence wind turbine noise when both sounds are audible. The results from the tests were compared to two loudness models. These two models have been developed at Cambridge University and are referred to as Moore's [32] respectively Glasberg's model [33]. Both models predict thresholds and partial loudness. The first model used third octave band levels as steady input. The second model used digital sound-files as input and calculated loudness at every 1 ms sample of the input files. These calculations were summed and a total loudness of the sound was presented.

The results from the threshold tests are showed in Fig. 10. As can be seen the experimental thresholds (circles) defined as S/N ratios ($L_{Aeq,1s,WT} - L_{Aeq,1s,BG}$) varied between -11.4 and -8.3 dB. The 95% confidence intervals are shown as

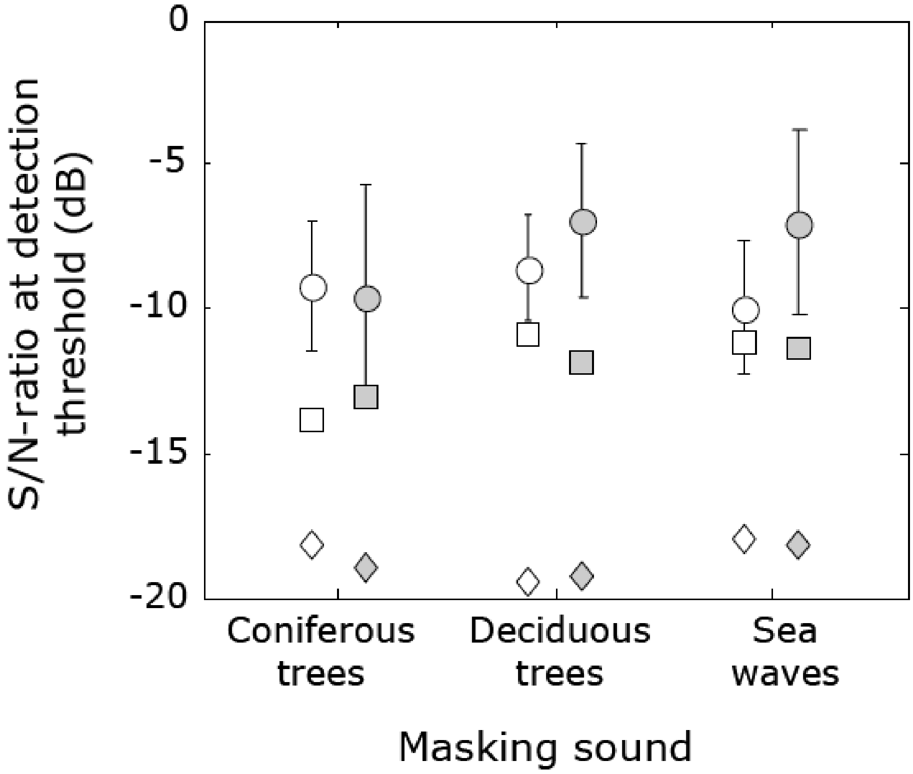

Figure 10: Detection thresholds for single wind turbine noise (open symbols) and multiple wind turbine noise (filled symbols) as heard in the presence of sounds from coniferous trees, deciduous tress or sea waves. Error bars indicate the 95 % confidence interval around the mean. Model predictions of Moore's and Glasberg's model are indicated with squares and diamonds, respectively.

error bars. Constant underestimations of the empirical thresholds are shown by the predictions. Moore's model (squares) showed an average underestimation of 2.4 dB for the single wind turbine noise and 2.8 dB for the multiple wind turbine noise. Glasberg's model (diamonds) showed even larger differences between experimental and predicted thresholds. For single wind turbine noise the average differences were between 9.0 dB and 9.5 dB for multiple wind turbine noise.

Results from the partial loudness test are shown in Fig. 11. The partial masking, L_{pl} was expressed as the subtraction of the perceived loudness by the stimuli sound level, $L_{matched} - L_{comparison}$. The three diagrams in Fig. 11 show results from one background each. The partial making of the experiment are shown as circles with 95% confidence intervals as error bars. The masking effect at 0 dB S/N ratio is around 5 dB for all combinations. This means that the wind turbine sounds were perceived as 5 dB less than it actually was. For higher S/N ratios the masking effect weakens gradually. Both Moore's and Glasberg's model predicts a greater effect of partial masking for all the S/N-ratios included in the experiment. All the predictions for the single wind turbine were below the 95% confidence intervals of the empirical L_{PL}-values. For single wind turbine noise the average difference between the empirical L_{PL}-values and predictions from Moore's model is 5.1 dB. The corresponding mean value for Glasberg's model is 7.5 dB. Predictions of multiple wind turbine noise showed better resemblance to experimental values. Moore's model underestimated L_{PL} on average by 4.0 dB while Glasberg's model showed mean underestimations of 4.6 dB.

To conclude: the results suggest that existing models of partial masking overestimate the ability to conceal wind turbine noise in ambient sounds. This may partly be due to informational masking. There were no great differences in the masking ability of the three sources or in the tendency of the two wind turbine noises to be masked. The experiment only included one instance of each source category. Therefore, the general applicability of the result needs to be evaluated in further studies including other natural sounds and wind turbine noises. Nevertheless, an important message of the present study is that masking of wind turbine noise by adding "positive" natural sounds may be a useful soundscape design tool. This would be especially relevant for quiet areas where wind turbine noise typically is perceived as highly unwanted, even at low levels. Examples of such environments would be national parks or areas used for recreational purposes where the absence of artificial noise, including wind turbine noise, is considered a significant value. Furthermore, the present results suggest that guideline values for wind turbine noise may benefit from being defined in terms of threshold levels or partial masking levels. This approach would be better than guideline values in terms of absolute wind turbine noise levels, since the perceived loudness of a given wind turbine level may vary considerably due to complete or partial masking by natural sound sources.

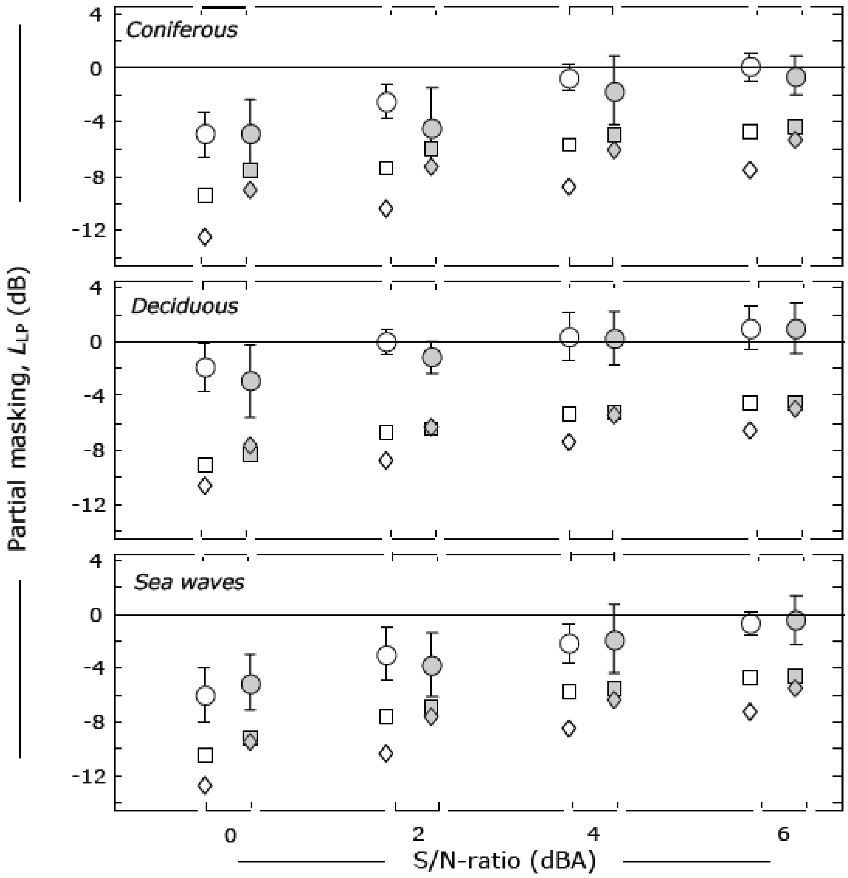

Figure 11: Level differences between equally loud wind turbine noises heard in the presence of masking sound and heard alone, as a function of S/N ratio. Results are shown for coniferous trees (upper diagram), deciduous trees (middle diagram) and sea waves (lower diagram), separately for single wind turbine noise (open symbols) and multiple wind turbine noise (filled symbols). Error bars indicate the 95 % confidence interval around the mean. Model predictions of Moore's and Glasberg's model are indicated with squares and diamonds, respectively.

8 Conclusion

The low allowed sound levels from wind turbines makes the masking by ambient sounds a key issue to understand and estimate the annoyance this noise source produce. The fixed limit of today's noise guidelines in Sweden may cause disturbance to nearby residents at some locations while the turbines is not even audible at other places. This penalizes the people living in environments with low ambient levels as well as the industry to harvest wind resources in an optimal way. This thesis aims at placing wind turbine noise in the ambient context which is considered necessary to correctly estimate the environmental impact from wind turbine noise.

The developments of models of natural ambient sounds have resulted in possibilities to predict the background sound level in coastal and forested areas. Thereby, measurements of ambient levels may be restricted in time and also the number of locations. Long range sound propagation over a sea surface is shown to be accurately described by the GFPE algorithm if local meteorological measurements are available. The meteorological conditions influence sound propagation. To avoid predictions of shadow-zones at upwind conditions turbulence should be included in the GFPE method. With this feature implemented the predictions show satisfactory agreement to the measured results. The psycho-acoustic test investigated the audibility of wind turbine noise when mixed with ambient sounds. From the experimental results it has been observed that the masking threshold occur when the wind turbine noise level is around 10 dB lower than the ambient sound levels. Furthermore, when wind turbine noise and the background sound have equal sound levels the wind turbine noise is perceived around 5 dB lower than if heard alone.

It is believed that this thesis can shed some light to the complex interactions between wind turbine noise and ambient sounds. However, this subject is still far from well understood. The wide scope of the thesis prevented the author to pursue research how the annoyance by wind turbines is altered by ambient noise. Other work could be done to verify the propagation model over hilly terrain and forested areas. Furthermore, conducting a comparative study with the GFPE model and for example the propagation template suggested by the Swedish Environmental Protection Agency [15] is considered interesting. This could be done to evaluate how much energy could be gained by adjusting the emitted noise to different meteorological conditions. The author hopes that the results in this thesis can be used as a tool to influence the guidelines and be used to improve the prediction tools used at wind turbine noise assessments.

Acknowledgments

The financial support from the Swedish Energy Agency through the wind energy foundation (Vindforsk II) contract number P 20134-3 is gratefully acknowledged. I would like to express my thanks to my supervisors professor Mats Åbom, adjunct professor Ilkka Karasalo, researcher Mats Nilsson and associate professor Shafiquzzaman Khan for their guidance through the course of this project. My thanks also remain to my colleagues at the Marcus Wallenberg Laboratory. I am also grateful to my family and friends for their cordial support. Finally, I would like to thank Karin for making rainy days wonderful and sunny days even better.

References

[1] P. Hedberg and S. Holmberg. Åsikter om energi och kärnkraft (opinions of energy and nuclear power). Technical report, SOM-Institutet, Göteborg University, 2009.

[2] J. F. Manwell J. G. McGovan and A. L. Rogers. *Wind Energy Explained*. John Wiley & Sons, New York, 2002.

[3] www.repower.de/index.php?id=237&L=1 (date last viewed 13/3/09).

[4] European Wind Energy Association. Ewea's response to the european commission's green paper. Technical report, (COM (2006) 275 Final), 2007.

[5] E. Pedersen and K. Persson Waye. Perception and annoyance due to wind turbine noise—a dose–response relationship. *The Journal of the Acoustical Society of America*, 116(6):3460–3470, 2004.

[6] B. Berglund and M. E. Nilsson. Total and source-specific loudness of singular and combined traffic sounds. Archives of the center for sensory research, 6(3) 2001.

[7] O. Fégeant. Wind-induced vegetation noise. part 1: A prediction model. *Acta Acustica*, 85:228–240, 1999.

[8] O. Fégeant. Wind-induced vegetation noise. part 2: Field measurements. *Acta Acustica*, 85:241–249, 1999.

[9] P. T. Manning. The environmental impact of the use of large wind turbines. *Wind Engineering*, 7(1), 1983.

[10] F. W. Grosveld H. H. Hubbard and K. P. Shepherd. Noise characteristics of large wind turbine generators. *Noise Control Engineering*, 21:21–29, 1983.

[11] TA-Lärm:. Technische anleitung zum schutz gegen lärm (technical guideline for noise protection). Technical Report Stand. GMBI. S. 503, Germany, 1998. (in German).

[12] J. Jakobsen and T. H. Pedersen. Stoj fra vindmoller og vindstojens maskerende virkning. Technical report, Lydtekniskt institut, Lyngby, 1989. Report number 141 (in Danish).

[13] A. W. Bezemer et al. Handleiding meten en rekenen industrielawaai (manual for measuring and calculating industrial noise). Technical Report 53-86, Den Haag, 1999. (in Dutch).

[14] R. Meir et al. The assessment and rating of noise from wind farms. Technical Report ETSU-R-97, ETSU, Department of Trade and Industry, 1996.

[15] S. Ljunggren. Ljud från vindkraftverk (sound from wind turbines). Technical Report 6241, Boverket, Energimyndigheten & Naturvårdsverket, Sweden, 2001.

[16] M. Sneddon et al. Measurements and analysis of the indigenous sound environment of coniferous forests. Technical report, BBN System and Technologies, 1994. NPOA Report No. 91-1, BBN Report No.7210.

[17] O. Fégeant. Masking of wind turbine noise: Influence of wind turbulence on ambient noise fluctuations. Technical Report 2002:12, Department of Civil and Architectural Engineering, Royal Institute of Technology, Sweden, 2002.

[18] J. Bouma F. van den Berg, E. Pedersen and R. Bakker. Windfarmperception, visual and acoustic impact of wind turbine farms on residents. Technical report, EU project: FP6-2005-Science-and-Society-20 Specific Support Action Project no. 044628, 2008.

[19] A. Prosperetti. Bubble-related ambient noise in the ocean. *J. Acoust. Soc. Am.*, 84:1042–1054, 1988.

[20] A. R. Kolaini. Sound radiation by waves in salt water. *J. Acoust. Soc. Am.*, 103:300–308, 1998.

[21] G. B. Deane. Sound generation and air entrainment by breaking waves in the surf zone. *J. Acoust. Soc. Am.*, 102:2671–2689, 1997.

[22] K. E. Gilbert and X. Di. A fast green's function method for one-way sound propagation in the atmosphere. *Journal of the Acoustical Society of America*, 94:2343–2352, 1993.

[23] E. M. Salomons. Improved greens function parabolic equation method for atmospheric sound propagation. *Journal of the Acoustical Society of America*, 104:100–111, 1998.

[24] L. Johansson. Sound propagation around off-shore wind turbines -long-range parabolic equation calculations for baltic sea conditions. Technical report, Licentiate thesis, KTH/ Building sciences, 2003.

[25] International Organization for Standardization, Geneva, Switzerland. *ISO/DIS 9613-1: Attenuation of sound during propagation outdoors- Part 1: Atmospheric absorption*, 1995.

[26] International Organization for Standardization, Geneva, Switzerland. *ISO/DIS 9613-2: Attenuation of sound during propagation outdoors- Part 2: General method of calculation*, 1996.

[27] A. K. Blackadar. Boundary layer wind maxima and their significance for the growth of nocturnal inversions. *Bulletin American Meteorological Society*, 38:283–290, 1957.

[28] M. E. Nilsson. *Perception of Traffic Sounds in Combination*. PhD thesis, Stockholm University and Karolinska Institutet, 2001.

[29] M. M. Green and J. A. Swets. *Signal Detection Theory and Psychophysics*. Krieger Publishing, New York, 2nd edition, 1974.

[30] O. Fégeant. On the masking of wind turbine noise by ambient noise. In *European Wind Energy Conference, EWEC´99*, pages 184–188, 1999. Nice, France.

[31] C. S. Watson. Some comments on informational masking. *Acta Acustica united with Acustica*, 91:502–512, 2005.

[32] B. R. Glasberg B. C. J. Moore and T. Baer. A model for the prediction of thresholds, loudness and partial loudness. *Journal of the Audio Engineering Society*, 45:224–240, 1997.

[33] B. R. Glasberg and B. C. J. Moore. Development and evaluation of a model for predicting the audibility of time-varying sounds in the presence of background sounds. *Journal of Audio Engineering Society*, 53:906–918, 2005.

[34] G. T. Fechner. *Elements der Psykophysik*. Breitkopf and Härterl, 1876.

[35] E. Zwicker and H. Fastl. *Psychoacoustics: Facts and Models*. Springer-Verlag, Berlin, 2001.

[36] K. R. Johnson R. Carhart, T. W. Tillman. Effects of interaural time delays on masking by two competing signals. *J. Acoust. Soc. Am.*, 43:1223–1230, 1968.

[37] E. S. Greetis R. Carhart, T. W. Tillman. Perceptual masking in multiple sound backgrounds. *J. Acoust. Soc. Am.*, 45:694–703, 1969.

[38] I. Pollack. Auditory informational masking. In *J. Acoust. Soc. Am. 57, Suppl. 1, 85*, 1975.

[39] B. D. Simpson D. S. Brungart. The effects of spatial separation in distance on the informational and energetic masking of a nearby speech signal. *J. Acoust. Soc. Am*, 112:664–676, 2002.

[40] M. R. Callahan F. L. Wightman: R. A. Lutfi, D. J. Kistler. Psychometric functions for informational masking. *J.Acoust. Soc. Am*, 114:32733282, 2003.

[41] T. L. Arbogast D. S. Brungart B. D. Simpson J. G. Kidd, C. R. Mason. Informational masking caused by contralateral stimulation. *Journal of Acoustical Society of America*, 113:15941603, 2003.

[42] E. Öhrström K. Persson Waye and M. Björkman. Buller och bullerstrningar från vindkraftverk (noise and noise annayance from wind turbines). Technical report, Avdelningen för Miljömedicin, Göteborgs universitet, 1997.

[43] A. L. Brown and A. Muhar. An approach to the acoustic design of outdoor space. *Journal of Environmental Planning and Management*, 47:827–842, 2004.

[44] J. C. Kaimal and J. J. Finnigan. *Atmospheric Boundary Layer Flows*. Oxford University Press, New York, 1994.

[45] K. Törnblom. Thermally driven wind modification in coastal areas and its influence on sound propagation with application to wind power. Technical report, Department of Earth Sciences, Uppsala University, 2006.

[46] International Organization for Standardization, Geneva, Switzerland. *ISO 389-7:2005 Acoustics Standard reference zero for the calibration of pure-tone air conduction audiometers, Part 7 Reference threshold of hearing under free-field and diffuse-field listening conditions*, 2005.