Masking of Wind Turbine Sound
by Ambient Noise

Karl Bolin

Stockholm 2006
Kungliga Tekniska Högskolan
School of Engineering Sciences
Department of Aeronautical and Vehicle Engineering
The Marcus Wallenberg Laboratory for Sound and Vibration Research

<table>
<thead>
<tr>
<th>Postal address</th>
<th>Visiting address</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Royal Institute of Technology</td>
<td>Teknikringen 8</td>
<td>Tel: +46 8 790 92 02</td>
</tr>
<tr>
<td>MWL / AVE</td>
<td>Stockholm</td>
<td>Fax: +46 8 790 61 22</td>
</tr>
<tr>
<td>SE-100 44 Stockholm</td>
<td></td>
<td>Email: <a href="mailto:kbolin@kth.se">kbolin@kth.se</a></td>
</tr>
<tr>
<td>Sweden</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Akademisk avhandling som med tillstånd av Kungliga Tekniska Högskolan i Stockholm framläggs till offentlig granskning för avläggande av teknologielicentiatexamen torsdagen den 14:e december 2006, kl 13.00 i sal MWL 74, Teknikringen 8, KTH, Stockholm.
TRITA-AVE -2006:86
ISSN -1651-7660
©Karl Bolin, November 2006
Abstract

Two aspects of ambient noise masking of sound from wind turbines are highlighted: the development of a prediction model for vegetation noise and the relative levels of ambient noise needed to mask wind turbine sound. The prediction model for vegetation noise has been compared with an earlier method with notable improvement, turbulent wind speeds are combined with the prediction model and a new model describing noise from deleafed trees are presented. A loudness test suggests that annoyance will occur at levels where the wind turbine noise exceed natural ambient noise by 3 dBA or more.
Licentiate thesis

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


Material from paper A and paper B have been presented at the conference Wind Turbine Noise 2005 in Berlin, Germany.

Division of work between the authors:
In paper C the theoretical and experimental work presented in the article, except for the analysis of variance, was performed by Karl Bolin under the supervision of Shafiquzzaman Khan. Both authors contributed to the writing of the article.
Contents

1 Introduction 1
2 Summary of papers 3
3 Future work 7
4 Acknowledgments 7
1 Introduction

Natural sounds have, since the beginning of our time, been a part of the environmental noise surrounding us humans. In rural areas the sound from wind flowing through vegetation would have been the dominating sound source, sometimes interrupted by human noise from craftsmen, a barking dog or bellowing cows. In coastal regions these sounds were accompanied by the sounds from waves breaking at the shorelines. This benign soundscape, constant for thousands of years, with the highest loudness produced by thunder or other rare natural phenomenas 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 [1] and in large parts of the developed world. This source has seriously altered the environment in many rural areas and further deterioration is indeed undesired. Today another emerging man made noise source are the wind turbine plants, these will grow in an increasing pace in the forthcoming years as signing states of the Kyoto protocol needs to fulfill their promises to decrease greenhouse gases. This expansion will be particularly rapid in the offshore niche as large wind-farms are planned in several countries. This could lead to noise pollution along coasts and inside recreation areas, regions invaluable for recreational purposes for large populations.

The earliest major commercial wind turbine development was sited in California following the Oil Crisis in the mid 1970s. In the subsequent decade the first articles regarding noise annoyance from large wind turbines were published by Manning [2] and Hubbard et al. [3]. Much research has been conducted since these papers to arrive at the present knowledge level about 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 present noise is mainly caused by broad band aerodynamic noise from the blades close to a turbine. This produce a distinct "swooshing" a sound similar to distant aircraft noise.

Different noise emission regulations exist in Europe, three basic strategies are the German, Dutch and British, respectively, which are described below. The German noise standard [4] allows for a noise imission of 45 dBA. This simple procedure will almost certainly result in suboptimal power output especially at higher wind speeds, because the ambient noise level usually increase faster than the turbine noise, thereby increasing the masking probability [5]. The Dutch noise regulation [6] 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 noise levels should be set low to avoid annoyance. The assumption that ambient noise levels
are approximately the same in different locations could be valid in a homogenous landscape like the Dutch farmland but many other countries have larger deviations in the rural landscape resulting in large variations in noise levels at 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 [7] allows for 5 dB higher turbine sound level than the measured background noise levels 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.

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. Although measurements of ambient noise levels are performed on a routine basis 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 [8] examines the noise generation from mixed coniferous forests in California and all year measurements of vegetation noise were performed by Jakobsen and Pedersen in [5]. However, Fégeant proposed the first semi-empirical prediction model of vegetation noise in [9] and [10] valid for different tree species and vegetation geometries. This analysis was validated for cases of non-turbulent flow. Further work by Fégeant [11] stressed the importance of wind turbulence causing variations in the level of vegetation noise. However, measurements have only been performed at wind speeds of 7 m/s and below [10], confirmation of the theory above these conditions is considered necessary in order to predict the noise at higher wind speeds. Furthermore the analytical expressions in [9] are not suited to estimate noise 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 in paper B which satisfactorily estimate the time fluctuations of vegetation noise. The question of when vegetation noise mask wind turbine sound were estimated by Fégeant [12] by calculating the detectivity index. However the obvious similarities between the broadband noise of vegetation and wind turbine sound, makes it interesting to apply modern psycho-acoustic models [13] [14]. Therefore a laboratory study has been performed in paper C to investigate the masking threshold and partial loudness of mixed ambient noise and wind turbine sound. Apart from the vegetation noise the masking potential of sea wave noise 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.
2 Summary of papers

Paper A- Prediction method for vegetation noise

A model describing the noise generation from vegetation is presented. The research by Fégeant [9] and [10] is refined to better agree with measurements. A semi-discrete model is proposed, this approach is better suited to process time fluctuating wind, turbulence, compared to the analytical model presented by Fégeant. Furthermore complex vegetation sources can easily be modeled. Sound generation from trees without foliage ("deleafed") are added and an all year spectra for sound from deciduous trees is proposed. The non-leafed sound spectrum is characterized by flow acoustic dipole sources when wind flows through the canopy as can be seen in Figure 1.

A term is added to the coniferous sound model by Fégeant to account for the aero-acoustic dipole sources when the wind flows around the branches and also to account for structural vibrations in moving canopy elements. These adjustments improve the spectral resemblance between predictions and measurements and also allows for estimation of all year deciduous sound level predictions. When compared to the Fégeant model the new model shows higher accuracy to estimate measured results at three locations, especially in the low frequency region see Figure 2. This is an important property because the masking potential of low frequency sound could be estimated with higher accuracy. Validations of the new model have also been performed at five locations including two without foliage. Measurements at wind speeds up to 12 m/s are also reported and compared to predictions with satisfying results this can be seen in Figure 3.

Paper B- Influence of turbulence and wind speed profiles on vegetation noise

The vertical wind velocity profile is modeled according to [15] and the implications of a changing velocity profile is evaluated. Wind turbulence also depend on atmospheric conditions, the variance of turbulence intensity are four times higher at unstable than in stable conditions [16], the implication of this on vegetation noise is severe because the emitted sound pressure are scaled with $p_{eff} \propto u^\chi$, where $\chi$ is a wind speed coefficient varying between 1.5 and 2.7 for different tree species [9]. The turbulence characteristic is combined with a simulation method that produce space- and time- correlated wind velocity time series. These data are inserted into a semi-discrete vegetation noise model to produce vegetation noise predictions capable to account for turbulence and changing vertical velocity profile.
Vegetation noise measurements from three locations are compared with simulations. One- and three-dimensional turbulence models have been used for the simulations. The observed similarity between one dimension and three dimension turbulence models indicate that the turbulence perpendicular to the mean wind direction can be neglected when estimating fluctuations in vegetation noise. Satisfactory agreement between time variations in the measurements and simulations are shown, see table 1, this despite the relatively short measurement periods of 20 minutes. An estimation method of vegetation noise fluctuations proposed in [11] estimate the standard deviation of A-weighed sound pressure level by 6.2 dBA compared to performed measurements with standard deviations of 3.0 dBA and are therefore considered not accurate enough.

The papers conclusion is that atmospheric conditions and turbulence have large effect on vegetation noise. Modeling this sound source without accounting for these factors could result in serious misjudgment in the masking potential of vegetation sounds on disturbing noise sources. It is therefore suggested that accurate wind models, including turbulence, should be used when estimating vegetation noise according to the semi discrete model in paper A.

**Paper C- Determining the potentiality of masking wind turbine noise using natural ambient noise**

This article examines the masking potentiality of wind turbine noise in the presence of three natural ambient noises, namely vegetations (coniferous and deciduous) and sea wave noises. Four different listening tests were performed by 36 subjects. The first two tests determine the threshold of wind turbine noise in the presence of the natural ambient noise. The third test examine the perceived proportion of wind turbine and natural ambient noise at various S/N ratios (S is wind turbine noise and N is natural ambient noise). The last test investigate the partial loudness of wind turbine noise in the presence of natural ambient noise. Results of the threshold test showed that the average masking threshold varied from S/N-ratios of -5.3 dBA to -2.6 dBA, where coniferous noise revealed better masking potentiality than the other natural ambient noises (deciduous and sea wave). The third test showed that the proportion of wind turbine noise is perceived as less than 50% of the total noise at S/N ratios of 3 dBA and below. The partial loudness test indicated that the observed partial loudness was higher in all S/N ratios compared to the existing partial loudness model [13] [14].
Figure 1: Third octave band noise spectra (sound power) in dB. Measurements (o) and prediction (—) for deleafed birch at a wind speed of 11.5 m/s. Note the peak corresponding to Strouhal-separation around the branches.

Figure 2: Sound pressure level in third octave bands at \( u = 4.4 \) m/s. (●) Measurement, (—) Prediction by Bolin, (•-•) Prediction by Fêgeant. Overview and third octave band sound pressure levels from the edge of aspens, site 5 in [17].
Figure 3: Third octave band spectrum of sound pressure levels. (-o-) measurements and (—) predictions respectively at  \( u=8.3 \) m/s (—) and at  \( u=4.6 \) m/s (- - -).

<table>
<thead>
<tr>
<th></th>
<th>Measurement</th>
<th>3D Simulation</th>
<th>1D Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( U ) (m/s)</td>
<td>( L_A ) (dBA)</td>
<td>( U ) (m/s)</td>
</tr>
<tr>
<td>Site 1</td>
<td>( \bar{x} )</td>
<td>5.1 55.2</td>
<td>5.2 54.1</td>
</tr>
<tr>
<td></td>
<td>( \sigma_x )</td>
<td>1.7 4.0</td>
<td>1.8 2.8</td>
</tr>
<tr>
<td>Site 2</td>
<td>( \bar{x} )</td>
<td>6.3 47.2</td>
<td>6.3 50.9</td>
</tr>
<tr>
<td></td>
<td>( \sigma_x )</td>
<td>1.5 3.0</td>
<td>1.6 3.4</td>
</tr>
<tr>
<td>Site 3 Mic 1</td>
<td>( \bar{x} )</td>
<td>5.2 56.8</td>
<td>5.2 56.2</td>
</tr>
<tr>
<td></td>
<td>( \sigma_x )</td>
<td>1.7 2.6</td>
<td>1.5 2.6</td>
</tr>
<tr>
<td>Site 3 Mic 2</td>
<td>( \bar{x} )</td>
<td>5.2 59.5</td>
<td>5.2 56.9</td>
</tr>
<tr>
<td></td>
<td>( \sigma_x )</td>
<td>1.7 5.2</td>
<td>1.8 2.8</td>
</tr>
</tbody>
</table>

Table 1: Measured wind speed and sound levels, \( \bar{x} \) denote average values and \( \sigma_x \) standard deviation.
Figure 4: Proportion of sound perceived as wind turbine noise for different S/N-ratios, average values and confidence intervals of 95% are shown.

3 Future work

Future work consists in creating a semi-empirical model for predicting sea wave noise. This is considered important as offshore wind turbine farms are planned or already under construction in many parts of Europe. In the psycho-acoustic field tests to explicitly evaluate the annoyance should be performed and also a larger number of subjects should participate. In addition a new partial loudness model for wind turbine noise should be developed.

4 Acknowledgments

The financial support from the Swedish wind energy foundation (VINDFORSK) contract number 20134-2 is gratefully acknowledged. I would like to express my thanks to my supervisors professor Mats Åbom 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


