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Title: Wind turbine noise exposure in a complex terrain

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Abstract

This paper presents results from a computational study of sound propagation from a wind turbine at a site in Northern Sweden. The landscape surrounding the site is complex with varying ground altitude as well as surface conditions. The objective of the study is to investigate variations of the noise dosage exposure on the ground with varying atmospheric and ground conditions at time scales extending from diurnal to seasonal. Two different sound propagation models, based on a parabolic equation approximation and a hybrid ray-tracing/Gaussian beam technique, respectively, are used. Meteorological input from the HIRLAM prognosis model, and geographical data on altitude and terrain type from digital maps, are used for input to the propagation models. The results are compared to the noise exposure obtained assuming a spherical spreading assumption as in the ISO9613 standard.

1. Introduction

The current state of computer science and numerical models combined with geographical and meteorological databases allows for a dramatic shift of noise dose assessments from wind turbine noise. Instead of using simple archaic procedures to determine noise propagation at specific meteorological conditions it has now become possible to process large amount of environmental data to be used as input for numerical schemes far more accurate at non-standardized weather and ground conditions. This paper is an investigation of the possibilities to acquire a noise dose from high performing calculations of noise propagation from a wind turbine site at a hilly, forested terrain in the northern part of Sweden. Several different numerical solvers are used which enables comparison between different methods as well as highlighting the methods strengths and weaknesses.

2. Method

2.1 Noise dose from wind turbines

Varying sounds is something inherent of the wind turbine noise issue. These alterations are depending on the source sound generation and directivity and also on the current meteorological conditions causing changing propagation paths. Annoyance is aroused by noise peaks when these factors are giving strong emission and unfortunate sound propagation. Therefore, noise distributions are essential to estimate annoyance from wind turbine sound. As has earlier been stated (van den Berg 2004 & Davies 2007) these moment usually occur at evenings or nights which is explained by strong wind gradients causing downward refraction of the sound combined with low levels of masking noise. Consequently a nominal or an average noise dose is probably not as representative as a measure of the noise dose in the worst case scenarios which could be represented by for example the L_{A10} percentile i.e. the noise level at the highest 10% of the time. To calculate such dose measures more accurate noise propagation algorithms than the ISO 9613 will have to be implemented and the authors of the current paper as well as other researchers Van Den Eerden (2008), Plovsing (2009), Sondergaard & Plovsing (2009) are currently working in this area.

2.2 Data acquisition

Sound propagation is depending upon environmental parameters to be computed correctly. Ground altitude and acoustic impedance are determining the amount of ground reflection that can be expected. Diffraction of sound waves is caused by changing sound speeds in the propagation media (air) and consequently knowledge of the sound speed profile spatial and temporal variations is also a prerequisite to calculate sound propagation accurately.

Geographical databases provide information of ground height and ground cover in most of the industrialized world. The data used in this article have been retrieved from the database “Metria” covering all the territory in Sweden. Altitude data are specified by a 50x50 m grid and ground coverage data by 25x25 m and thus quite accurate pictures of the landscape around the wind turbine is available. Ground coverage data are not directly convertible to ground impedances and vast ground impedance measurements even less so. Therefore, a schematic procedure converting ground conditions to specific flow resistivity parameters according to the tables in Embleton *et al* (1983) are used as input into the model suggested by Delany & Bazley (1970).

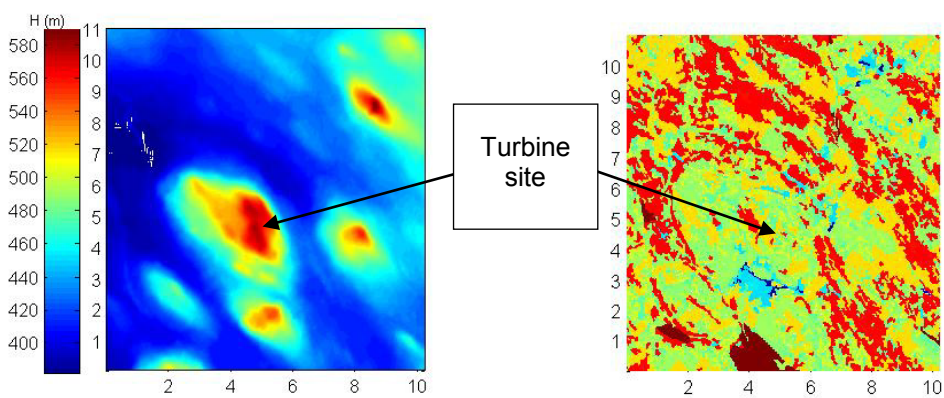
Meteorological information is readily available from the Swedish Meteorological and Hydrological Institute. These data come from a HIRLAM model which gives height profiles of wind velocity, temperature and humidity with grid size 5x5 km at every 3 hours. Although the model is not optimized for conditions at the boundary layer or near boundary layer the data have seasonal and daily variations and it is thus interesting to examine.

2.3 Site description

The wind turbine is located on a forested hill and was chosen because it has good wind resources, good grid capacity and long distance ~1 km to nearest dwelling (to the south). It is a 0.8 MW turbine with a hub height of 73 m and a rotor diameter of 53 m with an annual energy production estimated to $1.6*10^6$ kWh. As this paper do not investigate the acoustic source from turbines a coarse assumption that the wind turbine have a cut-on wind speed at 3 m/s at hub height and a cutoff wind speed at 15 m/s Enercon (2011) the turbine is assumed to generate as 98 dBA taken from a mean of 0.8 MW turbines Madsen & Pederson (2010). A terrain map is shown in figure 1. As can be observed most of the area is forested with only marginal fields around the villages Latikberg and Järvsö. The hill where the turbine is positioned has a steep north-eastern slope while the remaining sides are gentler. Several smaller hills around the wind turbine like Frostberget (east) and Bomsjöberget (south) could shield sound and therefore the terrain is demanding correct noise propagation into acoustic shadow zones.

Figure 1: Map of the wind turbine site with the red spot showing the location of the turbine. Houses are shown as black squares.

The altitude and ground conditions can be seen in figure 2. As can be observed the altitude at the turbine is approximately 600 m above sea level and the nearest dwelling 200 m below at a distance of ~1 km. The houses and fields at Latikberg in figure 1 are seen as blue and turquoise colors in figure 2 (b) while the lake South of Latikberg has a deep red color.



(a) (b)

Figure 2: Show the altitude (a) and ground data (b) from the geographical data base. The abscissa and ordinate represent distances in km. The wind turbine position is pointed out by arrows.

2.4 Treatment of environmental data

The sound propagation algorithms require the ground height and all atmospheric and ground parameters to be smooth functions of the spatial coordinates. Therefore the atmospheric and ground data are processed into smooth functions of (x,y,z) and (x,y), respectively, using variance-reducing B-splines, de Boor (1985). The sound propagation algorithms compute the soundfield in vertical planes through the source in which the effective sound speed – the sum of the sound speed and the wind speed in the direction of propagation – is a function of range r to the source and height z.

2.5 Sound propagation algorithms

Three different methods are described in this section. All of these are fundamentally different from each other. The first and most simplistic is the ISO 9613 (1996) comprised of a direct and reflected sound propagation rays without taking refraction into account. The second method is based on a numerical calculation of a parabolic equation derived from the Helmholtz equation while the third is a geometrical acoustics solution incorporating Gaussian beams. The first method is widely used at present moment but grossly simplifies the sound propagation while the latter ones are, although with elementary different approaches, capable of using irregular terrain as well as range dependent sound speed profiles. Consequently, it is believed by the authors that if these two calculations show similar results quite some faith could be trusted to the solutions.

ISO9613

Calculation results according to the ISO 9613 standard are shown in figure 3 Svewind (2006). As can be seen, the sound levels are concentric circles around the wind turbine with the largest (purple) circle representing 35 dBA and the innermost showing the 50 dBA curve. No concern is taken for the changing altitude or changing terrain in this method.

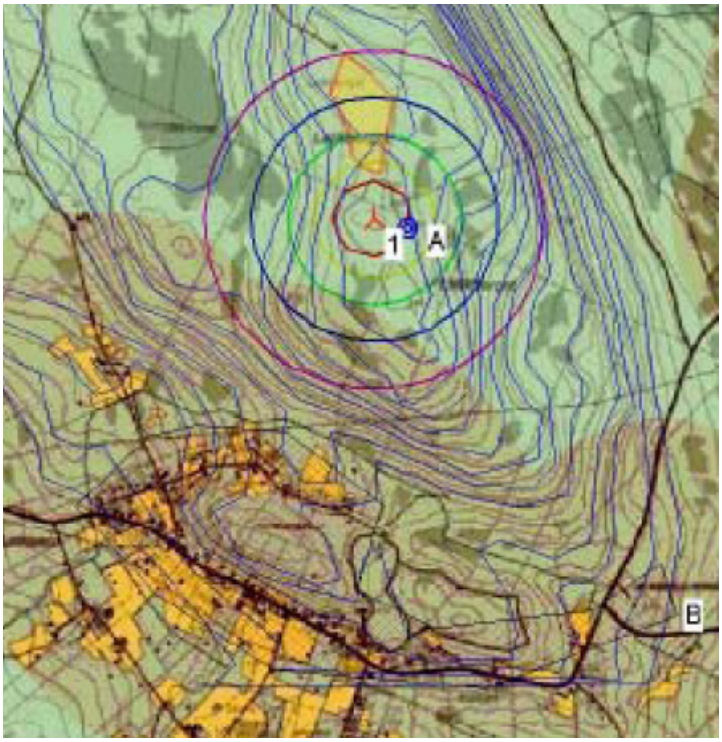


Figure 3: ISO 9613 calculation from Svewind (2006) of the sound level around the wind turbine. The innermost red circle denote 50 dBA, the green 43 dBA the blue 39 dBA and the purple 35 dBA. The fields around the village Latikberg can be seen as yellow blocks and the forest surrounding them is green.

Jeltsch Energy-conserving Parabolic Equation, JEPE

This computational method is based on a parabolic equation (PE) derived from the Helmholtz equation for frequency-domain soundfields. It is based on formulating the PE as a ordinary differential-algebraic (DA) system of equations by discretizing in space, and solving the DA-system by a fourth-order, strongly damped, scheme by Jeltsch (1977), see Karasalo & Sundström (1996) for further details. JEPE was originally developed for underwater acoustic applications and later adapted to atmospheric sound propagation by introducing a local artificial absorption layer Salomons (2003) as an approximation of the non-reflecting condition at the upper boundary. Irregular terrain is handled by using orthogonal boundary-adapted curvilinear coordinates Abrahamsson (1991), which simplifies the formulation of stable boundary conditions at the upper and lower boundaries. An adaptive range-step controlled by a local error estimate is used for marching in range.

Gaussian beams

The Gaussian beam summation method was developed in the early 1980s as a technique for avoiding the well known shortcomings of classical ray tracing

algorithms such as caustics and shadow zones. In the Gaussian beam method the rays are replaced by beams with amplitude given by a Gaussian function of distance to the ray and width as function of arc-length along the ray controlled by the equations of dynamic ray tracing. For a detailed description of the method the interested reader is referred to Popov (1982) and Gabillet & Schroeder (1993).

2.6 Noise dose calculation

To estimate the noise dose from the transmission losses from sound propagation calculations are calculated as follows:

1. Ground data are processed.
2. Meteorological data are processed at time T.
3. Calculating the transmission losses at 80 Hz from wind speeds at hub height between 3 to 15 m/s in 72 cross sections at every 5° angle. Then time T is propagated 6 hours and step 2 and 3 is looped until a complete year has past (except one day with missing data).
4. Assumption of omnidirectional spherical spreading from the hub. The acoustic power is assumed to 98 dBA at all included wind speeds. To acquire the sound pressure level at 1 m distance i. e. the starting condition of the transmission loss the sound power is reduced by 11 dB.
5. The calculated TLs in the different cross sections are subtracted from the L_p at 1 m distance and thus noise levels from that particular time is calculated.
6. Calculate equivalent, mean and 10-percentile sound levels from the results obtained in step 5.

This procedure simplifies the situation because only one frequency dependent transmission loss is performed at every time. More suitable would be to calculate sound transmission for several octave bands, know the wind speed depending source spectra and to take into account the sound source 3D directivity. However, the present paper emphasize the effects of sound propagation over complex terrain and the above stated generalizations are therefore considered of relatively small importance in this context although they certainly needs to be taken into account if more realistic noise doses are to be calculated.

3. Results

Comparison between the sound propagation methods

To compare the different numerical schemes the sound propagation at 80 Hz is examined. Shown in figure 4 are the sound speed profiles to the left and transmission loss for four different calculations at 180° (southern) propagation

direction to the right. A local maximum of the sound speed can be observed at 1.4 km and 1.3 km at respective ranges. Quite high resemblance between transmission losses are observed between Gaussian beams modeling and JEPE calculations but the ray tracing (without Gaussian beams) shows a shadow zone at 3 km distance. From these results and other calculations the similarity between Gaussian beams and JEPE solutions are good and therefore the first method is preferred for the complete dose calculation due to its' higher computational speed.

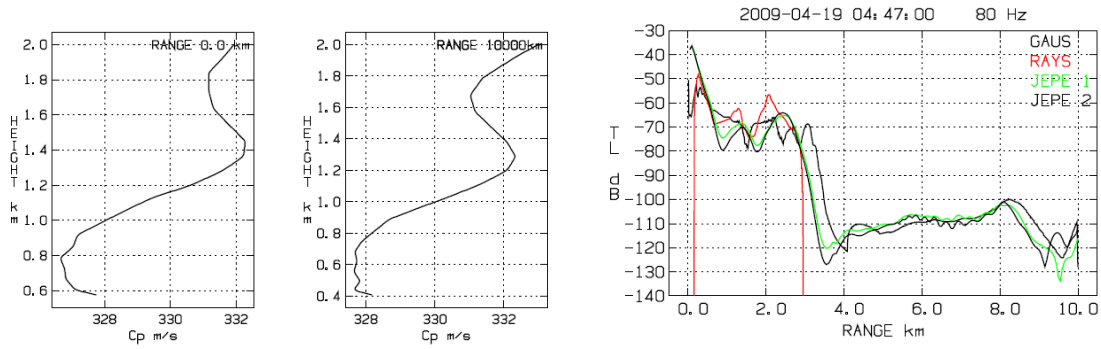


Figure 4: Sound speed profiles at 0 and 10 km distance and transmission loss plots from four different calculations to the right. The date is 19th April 2009 at 4:47 am and the frequency 80 Hz.

Noise dose calculations

This subsection show results from the calculations of sound propagation from the wind turbine every 6 hours for the entire year of 2009. These calculations are performed by the Gaussian beam algorithm. The sound levels are acquired by the procedure described in section 2.6. These 4*364 = 1454 calculations in different weather conditions required approximately 480 process hours (60 h on an 8 kernel computer).

Shown in figure 5 is a noise map of the average A-weighed sound level (L_A) from these calculations while figure 6 shows the equivalent level L_{Aeq} and figure 7 the 10-percentile distribution. As can be noticed the average sound pressure level over the period is low close to the turbine. This is a result of that the rays are limited to ±20° from the horizontal plane in order to increase the computational speed. If a detailed study of the region close to the turbine is considered interesting wider angles should also be included to increase the accuracy. The sound levels between 25 and 30 dB form concentric circles around the turbine site and are thus somewhat comparable to the ISO 9613 predictions although the levels are different.

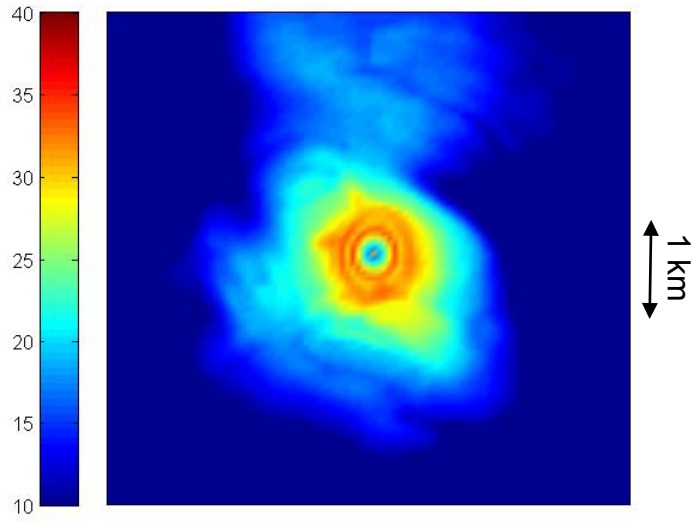


Figure 5: Noise map of L_A from the investigated wind turbine site. The colors show the average sound level around the wind turbine placed in the middle of the plot.

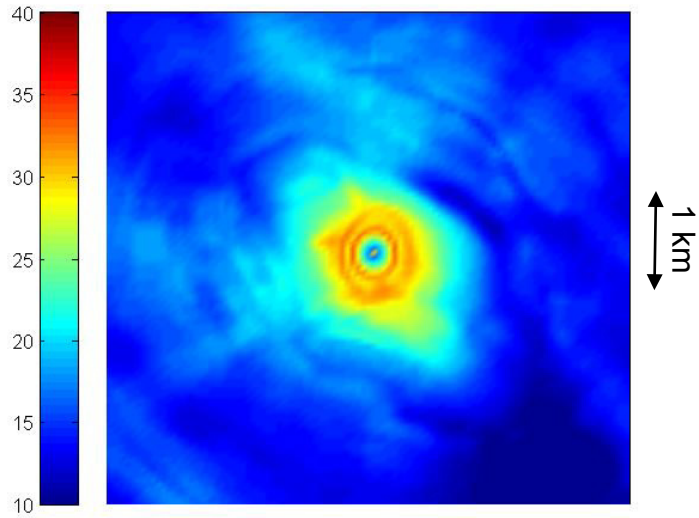


Figure 6: Displays the L_{Aeq} equivalent sound levels.

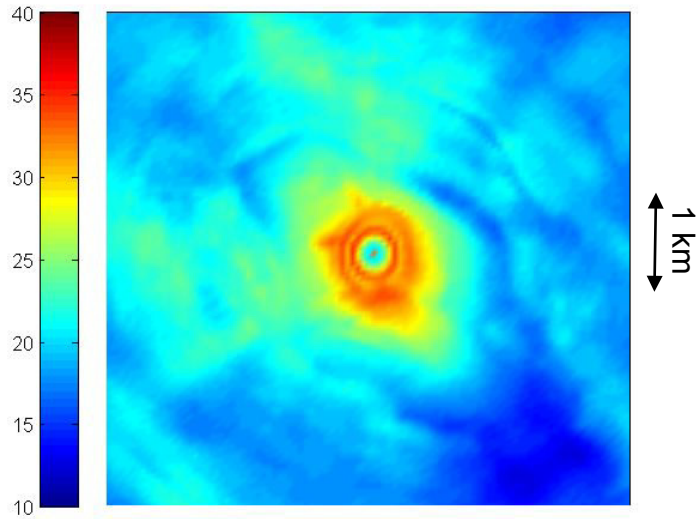


Figure 7: Noise map of the 10-percentile A-weighed sound level (L_{A10}).

Apart from noise maps, another interesting variable could be the histograms of distributions at points where noise annoyance might occur. Samples of such graphs are shown in figure 8 where the histograms from the four cardinal directions are shown at 1 km distance from the turbine. 20 % of the times the turbine is not running as seen by the bar at 0 dBA. The distributions differ quite significantly between the four directions. All distributions are centered round 20 dBA but the Southern and Western directions are more varied than the other two. When analyzing consequences of wind turbine noise these kinds of dose distributions could be a simple and straightforward procedure to reveal if sound peaks might appear and how often they could be expected.

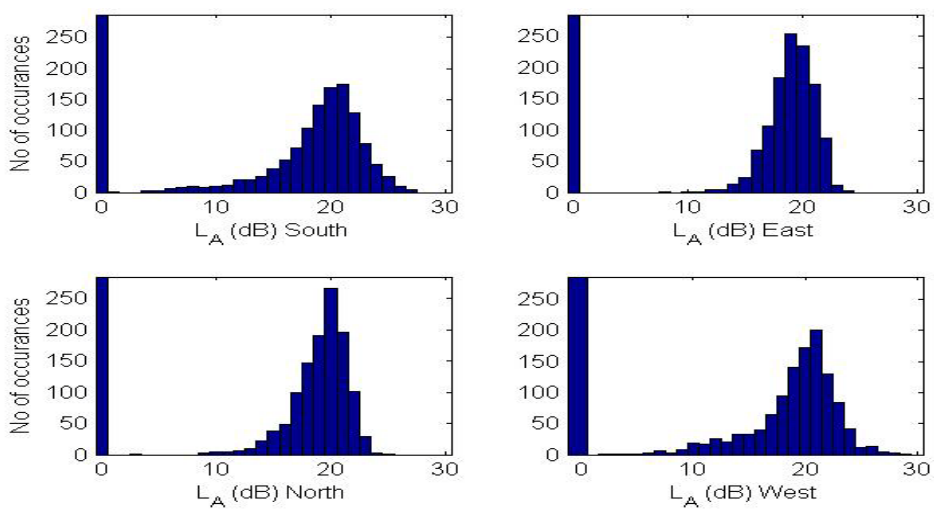


Figure 8: A-weighed sound pressure level distributions at 1 km distance to the turbine in the cardinal directions.

4. Conclusion

Advances in computer science have led to a point where calculations of noise doses from wind turbines are possible. Databases with information of altitude, ground conditions and meteorological data provide input parameters to estimate time varying sound propagation over long periods. The methodology described in this paper show promising results of delivering sound propagation mapping in complex terrain with weather conditions over yearly basis. This procedure allows for, apart from just calculating a nominal noise dose as in ISO 9613, to calculate the actual noise maps and noise distributions which could hopefully give an improved understanding and more accurate predictions when estimating the annoyance caused by wind turbines. Furthermore, this kind of calculations opens up for guidelines determined by the noise dose rather than the inaccurate estimations related to the ISO 9613 now in extensive use. This would be a procedure that, in the authors' opinions, would be much fairer than many of the present rules which could mean varying noise dose from

Acknowledgements

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