Prediction and Reduction of Noise from a 2.3 MW Wind Turbine

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Prediction and Reduction of Noise from a 2.3 MW Wind Turbine

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Abstract. We address the issue of noise emission from a 2.3 MW SWT-2.3-93 wind turbine and compare simulations from a semi-empirical acoustic model with measurements. The noise measurements were taken at the Høvsøre test site for large wind turbines. The acoustic model is based on the Blade-Element Momentum (BEM) technique and various semi-empirical acoustic relations. The comparison demonstrates a generally good agreement between predicted and measured noise levels. The acoustic model is further employed to carry out a parametrical study to optimize the performance/noise of the wind turbine by changing tip speed and pitch setting. We show that it is possible to reduce the noise level up to 2 dB(A) without sacrificing too much the power yield.

1. Introduction

Wind turbines are viewed with sympathy by most people. However, one of the main concerns for neighbors to planned wind farms is noise. This is not a surprise: experience has shown that people are worried about noise, more than anything else, when it comes to the creation of *anything* new, ranging from roads and shopping centers to night clubs, in their surrounding area.

In the planning stage of a wind farm, it is in most cases sufficient to utilize simple empirical prediction models, such as those included in most commercial packages, to predict the noise level. However, there have been cases where, for one or another reason, these predictions have failed leading to complaints (e.g. see [1]).

Although the emission of noise from wind turbines in most cases is smaller than that from other environmental noise sources, such as roads, airports and construction machinery, wind turbines are usually placed in rural environments, where the background noise typically is low. Thus, wind turbine noise is of great concern since it may be the only major noise source in rural districts.

Today, machinery noise is reduced efficiently by well-known engineering techniques, such as proper insulation of the nacelle. Traditionally, aerodynamic noise has been controlled by lowering the tip speed to a maximum of about 60 m/s, as the tip speed is the most significant parameter affecting aerodynamic noise. However, in recent years the biggest development of wind turbines has taken place offshore, with the result that the latest generation of wind turbines operate at tip speeds up to 80 m/s, indicating that noise again may be a problem with respect to public acceptance.

Studying noise from wind turbines is not a new field. Recently, however, its importance has grown so that it even needs its own dedicated conferences: the first conference on wind turbine noise took place in October 2005 in Berlin with a follow-up scheduled for 2007 in Lyon.

Through the years, several models have been proposed to explain and predict wind turbine noise. Some of the models are somewhat simplistic (e.g. [2-4]), whereas others make use of complex CFD solvers that have not yet matured to be applied in practice (e.g. [5]). As a compromise between computing speed and accuracy, the most commonly used models are based on semi-empirical relations. As basis, most models employ the experimental results on airfoil self-noise by Brooks, Pope and Marcolini [6]. These data, that can be directly used to predict wind turbine noise, are based on wind tunnel experiments of NACA 0012 airfoils.

In a previous work, we have developed a semi-empirical noise prediction model [7,8] using the scaling laws given in Brooks, Pope and Marcolini [6], together with the turbulence inflow model proposed by Amiet [9]. The model was tested successfully against a Bonus 300 kW wind turbine and was used in a parametrical study yielding many useful and interesting results.

Similar work, based on the results of [6], has been conducted by e.g. Fuglsang and Madsen [10], Moriarty and Migliore [11] and in the SIROCCO project [12]. This demonstrates that these prediction laws are widely accepted as the best available prediction tools.

The main goal of this paper is to validate the model against measurements of a MW wind turbine and to couple it with an optimization tool in order to optimize the operational conditions of wind turbines with respect to both performance and noise.

In section 2, we give a short description of the noise prediction model, including a summary of the main ingredients of the model. In section 3, we briefly report on some recent noise measurements and we validate our predictions against the obtained data. In section 4 we present the results from a parametrical optimization study, and in section 5 we summarize our conclusions.

2. The noise prediction model

In this report we treat only aerodynamic noise from wind turbines (i.e. mechanical noise is not considered). Aerodynamic noise can be divided into *airfoil self-noise* and *turbulence inflow noise*. The former is a result of the interaction of the boundary layer of the airfoil with the trailing edge and the latter results from the interaction of the existing turbulence in the wind with the airfoil.

In our model, the airfoil self-noise prediction is based on the functions given by Brooks, Pope and Marcolini [6]. In total, *five* airfoil self-noise mechanisms were identified and studied separately:

- Turbulent Boundary Layer Trailing Edge noise
- Separation-Stall noise
- Laminar Boundary Layer Vortex Shedding noise
- Tip Vortex Formation noise and
- Trailing Edge Bluntness Vortex Shedding noise

As a result, scaling laws were proposed, yielding the sound pressure level at the observer position as a function of frequency for the 1/3 octave band spectrum. The scaling laws for the different mechanisms are all of similar form:

$$SPL_i = 10\log\left(\frac{\delta_i^* M^{f(i)} L\overline{D}_h}{r^2}\right) + F_i(St) + G_i(Re) \tag{1}$$

where δ_i^* is the boundary layer displacement thickness, M is the Mach number, $f(i)$ is the raised power which depends on the particular noise mechanism i, L is the airfoil section semi-span, $\overline{D}_h$ is a sound directivity function and r is the distance to the observer. The additional terms $F_i(St)$ and $G_i(Re)$ are functions of the *Strouhal number* $St = f\delta^* / U$ and the *Reynolds number* Re. The nature of dependency is different for each noise mechanism but it is impressive that all the formulas look so much alike.

For turbulence inflow, a prediction equation based on the work of Amiet [9] has been implemented in the model:

$$L_p = 10\log\left(\rho_0^2 c_0^2 l \frac{\Delta L}{r^2} M^3 I^2 \hat{k}^3 \left(1+\hat{k}^2\right)^{-7/3}\right) + 58.4 + 10\log\left(\frac{K_c}{1+K_c}\right) \tag{2}$$

where l is a turbulence length scale, I is the turbulence intensity, ρ_0 is the density, c_0 the speed of sound, ΔL is the blade segment semi-span, $\hat{k}$ is a corrected wave length and K_c is a low frequency correction.

Taking into account all the variable dependencies, the problem of predicting the noise spectrum at a given observer position for a given airfoil reduces to identifying the following quantities:

- The boundary layer thickness δ^* at the trailing edge of the airfoil
- The relative wind speed defining M and Re
- The boundary layer transition type (forced or natural), leading to tripped or un-tripped flow
- Miscellaneous input parameters to the turbulence inflow noise model, such as turbulent length scale and intensity, in the model reduced to the knowledge of the height from the ground z and the roughness length z_o.

In this paper we do not go into the theory behind the empirical correlations, and for details about the nature of each of the modelled noise mechanisms we refer the reader to the original work of Brooks, Pope and Marcolini [6] and Amiet [9].

As mentioned above, an important parameter for the calculation of airfoil self-noise is the boundary layer thickness at the trailing edge. This is calculated by use of the program XFOIL [13]. It is important to note that the scaling laws shown above are deduced from experiments based only on the NACA 0012 airfoil. For this reason, an independent calculation of δ^* for each airfoil type is vital. This was done for a number of different values of Reynolds number and angle of attack and the computed boundary layer thickness was stored in a database and subsequently determined by interpolation.

Essentially, the code consists of a 'traditional' BEM code (see e.g. [14]), to compute the relative velocities along each blade element defining the rotor, coupled with the routines by [6] to predict the noise contribution for each noise source along the span of the rotor blades. In a few words, the prediction code works as follows. First, the relative velocities seen by the blade elements are computed, just like in an ordinary BEM computation. Next, a table look up in the boundary layer thickness database is made and the sound pressure level L_p and the noise spectrum at the observer position is calculated for each noise mechanism and for each blade element. Finally, the sound pressure levels are added for all elements, all blades and all mechanisms and converted to sound power levels L_w referring to the hub of the wind turbine.

The main advantage of the semi-empirical model is that it is fast to run, even on a PC, and that it gives surprisingly reliable results, as will be demonstrated in the following. It is also fairly easy to couple the prediction code to an optimisation algorithm and use it as a tool to optimize the rotor with respect to both performance and noise.

3. Noise measurements and model validation

The noise measurements were performed on a Siemens SWT-2.3-93 wind turbine at the Høvsøre Test Site for Large Wind Turbines. The measurements took place during two days, resulting in approximately 11 hours of data. Microphones were placed at four different positions, two downwind the rotor and two in the rotor plane, and the data were recorded simultaneously by all the microphones. Further, power production and wind speed, measured at hub height, were recorded in order to set the reference. The measurements were taken at different tip speeds and pitch settings. In order to check noise emission at off-design situations, the settings did not necessarily correspond to the settings at normal operational conditions.

In figure 1 we compare the computed Sound Power Level (SPL) with measurements as a function of wind speed for a turbine running at normal operational conditions. The measured data points are displayed together with a best fit and an 2σ interval, giving a 95% confidence. It is observed that the simulation over predicts the measurements with up to 2 dB, staying, however, within the 95% confidence interval.

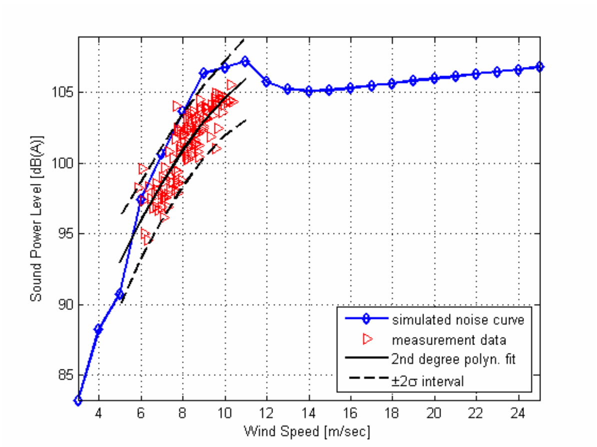

Figure 1: Comparison between computed SPL and measurements for the Siemens SWT-2.3-93 wind turbine operating at normal tip speed and pitch setting.

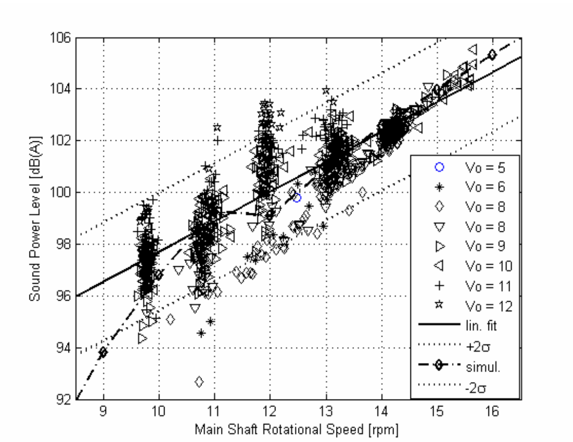

Figure 2: Comparison between computed SPL and measured data as function of rotational speed at various wind speeds.

The rotational velocity is the most important parameter affecting the noise production and it is therefore vital that the model captures the right ω-dependency. In figure 2, we compare the simulated SPL against measured data as function of rotational speed at different wind speeds, while keeping the pitch angle constant. A best fit together with an 2σ interval has been added to the measurements. All points have been binned with respect to wind speed and the simulation curve is for the mean measured wind speed.

We make three main observations: 1) There exists a linear relationship between the sound power level and the rotational speed; 2) For the same rotational velocity, higher wind speeds result in higher noise levels; 3) The comparison demonstrates that the model is capable of predicting the measurements.

In order to study the dependency of the noise level on the pitch setting, we present two graphs showing the SPL at different wind speeds and constant rotational speed. In figures 3 and 4 we show the results at a rotational speed of 17 RPM and 13 RPM, respectively. All simulations were made for a mean wind speed derived from the measured values. It should be noted that the tip speed tested in figure 3 is actually larger than the normal operational limit of the SWT-2.3-93.

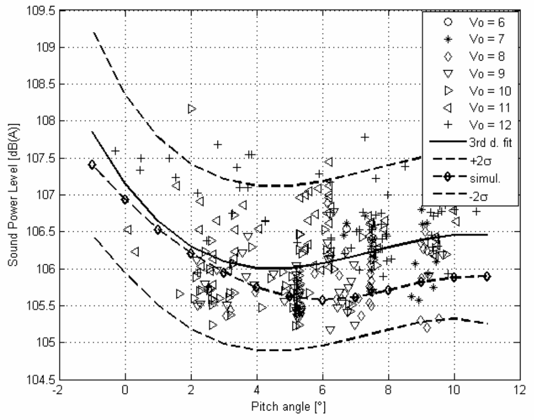

Figure 3: Comparison between computed SPL and measurements as function of pitch settings at different wind speeds and a high rotational speed of 17 RPM.

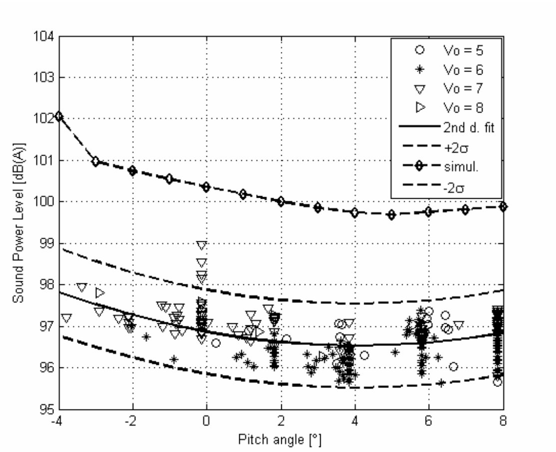

Figure 4: Comparison between computed SPL and measurements as function of pitch settings at different wind speeds and a medium rotational speed of 13 RPM.

From the figures we observe that the prediction at ω=17 RPM is in very good agreement with measurements. At ω=13 RPM, however, the measured level is over predicted by around 3 dB. A likely explanation for this is that the measured data at this particular experiment was dominated by a high background noise level that may have polluted the filtered data. Nevertheless, in both cases the noise clearly increases when decreasing the pitch angle. This is due to the increasing importance of the boundary layer separation noise mechanism, as the angle of attack becomes higher. This difference can be as high as 2 dB(A) for 5^o difference in pitch.

Except for broadband noise, it is important to test how the model predicts the frequency distribution in the 1/3 octave spectrum for different operational settings. In figure 5 we show a representative example in which a computed spectral distribution of SPL is compared to a measured distribution.

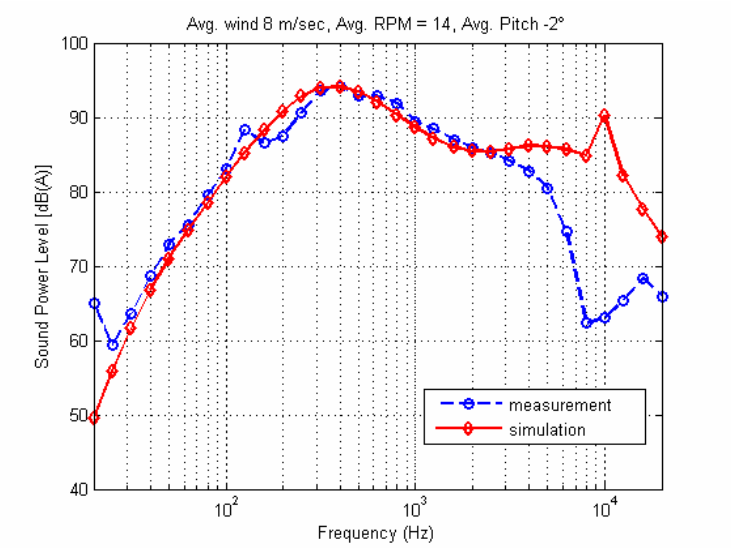

Figure 5: Spectral distribution of total SPL. The experimental spectrum is the average of all the measurement points (107 10sec averages in total) which had 13.5 RPM<ω<14.5 RPM, -3<θ<-1 and 7 m/s<Vo<9 m/s. The simulated spectrum is for the averaged setting i.e. ω=14 RPM, θ=-2 and Vo=8 m/s. This is a representative example of agreement between modelled and measured spectra.

Comparing the two curves, a good agreement is observed for frequencies between 10 and 3000 Hz. For higher frequencies, however, the simulation systematically over predicts the measurements. In fact, the measurements show that the noise level is negligible above 10 kHz, while the model predicts a level up to 90 dB(A). Analyzing this phenomenon more closely, it was found to be partly due to bluntness noise, which is tonal and predicts an unphysical high peak, and partly due to turbulence inflow noise, which turns out to be unreasonably high at these high frequencies. This indicates that the bluntness mechanism elaborated by Brooks, Pope and Marcolini [6] should be analyzed further and that there seems to be room for improvements. However, up to 3 kHz the computed distribution is everywhere in excellent agreement with the measured values.

4. Results of parametrical study

4.1. Simulation results

In figure 6 we show the result of a parametrical study in which predicted noise contours are shown as function of pitch angle and rotational speed. As expected, the noise level increases as we move to higher rotational velocities. However, the pitch angle also has an effect. At constant rotational speed, the noise increases as the pitch angle decreases (the angle of attack increases and the blade goes into stall). In figure 7 we present computed contour levels of total sound pressure as a function of radial distance in the rotor plane. The contour levels reflect in which part of the blade most noise is produced. As expected, most noise is generated at the tip, where the velocities are highest. However, we also observe a secondary maximum at 50% blade radius, where the blade becomes significantly blunt.

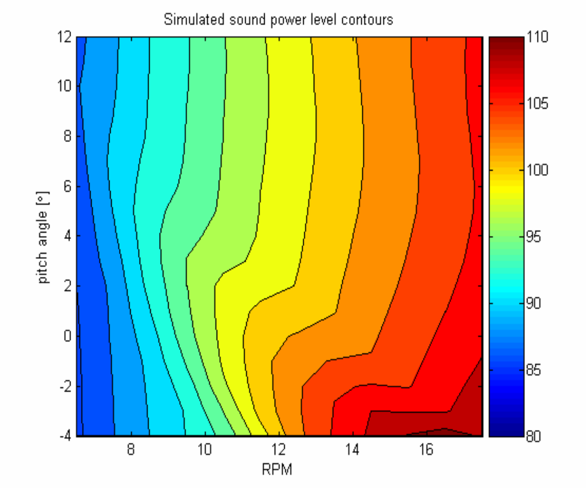

Figure 6: Computed noise contours (SPL) for the SWT-2.3-93 wind turbine operating at different settings. The simulation is for a wind speed of 10 m/sec.

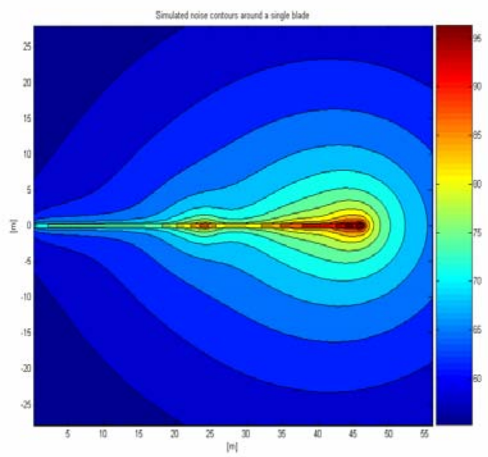

Figure 7: Computed noise contours (SPL) at different points in the rotor plane. Each point is computed by integrating the contribution from all blade elements and all noise sources.

4.2. Optimization of operating conditions

It is our purpose here to optimize the SWT-2.3-93 operation, by changing the rotational velocity and the pitch angle. As demonstrated by Fuglsang and Madsen [10], different optimization strategies exist. In the present work we either seek to minimize noise keeping the power at a constant minimum level or we maximize the power keeping the noise below an a priori defined level. While minimizing the noise level we try to lower L_w without sacrificing too much the power production. A strict constraint for the power would be 99% while a more relaxed would be 95% of the maximum power production. In power maximization, like the name implies, we try to maximize the power production, constraining however the noise not to exceed a maximum value. In the optimization we only include wind speeds in the range from 7 m/s to 15 m/s. The reason for this limitation is that at higher wind speeds the wind turbine noise gets masked by the increased background noise from trees, bushes, waves, etc, and that this interval probably is the most sensitive both with respect to power production and noise annoyance. The tip speed-pitch combination is optimized for *each* of the considered wind speeds separately. As optimization tool we employ the function **fmincon** that is a part of the MATLAB optimization toolbox and that is used for constrained non-linear optimization.

As in every optimization subject to limitations, the result is basically related to the constraints imposed to the optimization search. In our case, the optimization results were forced to obey two constraints: that the power should not exceed 2300 kW and that the driving torque should not exceed a certain limit, which would increase the damage probability of the gearbox. No other parameters, such as those related to loads or the control system, were taken into account.

4.2.1. *Noise minimization.* As explained above, we look for a combination of rotational velocity and pitch setting that leads to a less noisy operation, by constraining the power loss that we are willing to trade for this noise reduction. We have performed optimizations for two different constraints in power: 99% and 95% of the power achieved at normal operational settings. In figure 9 we show the reduction in sound power level SWL, measured in dB(A), for these two cases. We observe that considerable reduction in noise (2 dB) can be obtained by losing only 1% in power at wind speeds up to 9 m/s. This gain however exhibits a minimum of 0.4 dB at 11 m/s. Unfortunately, this is also the location at which the noise level is maximum. In order to obtain a significant noise reduction at wind speeds higher than 11 m/s, more sacrifices in power (5%) are needed.

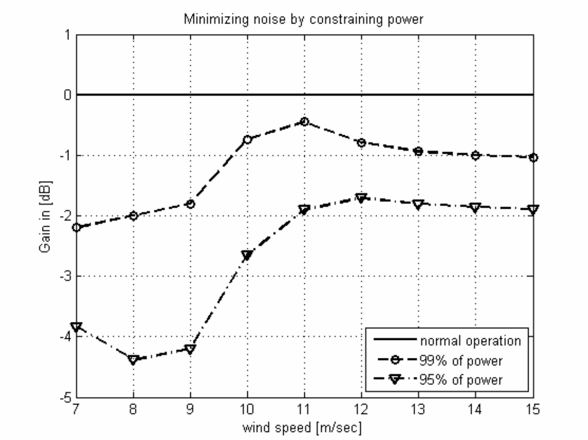

Figure 8: Noise reduction in dB(A) as a result of optimization at different wind speeds.

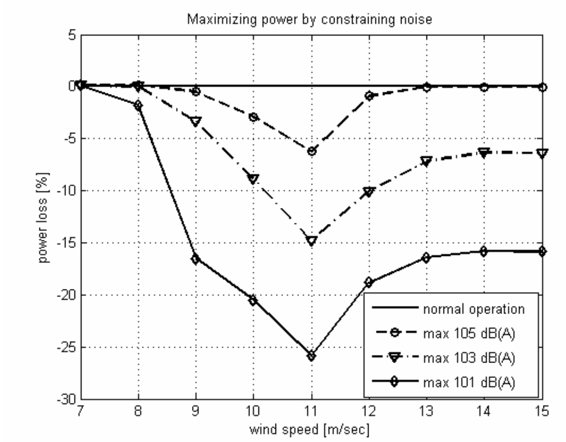

Figure 9: optimized (minimum) power losses for different noise constraints at different wind speeds. The stricter the constraint, the lower the power production. The maximum losses are at 11 m/s.

4.2.2. Power maximization. In this type of optimization, we force an upper limit in noise and look for the optimum settings that will maximize power. This might for example be a limit that is imposed by legislation and that cannot be trespassed (e.g. in combination with the distance to the nearest dwellings). In a sense, this type of optimization is more realistic, since one might not want to reduce the power yield at 8 m/sec, and only accept the minimum reduction in power at 11 m/sec. However, the study in the previous section can still be valuable in its conclusions if all results are given in relative terms. In figure 9 we depict the power loss (in %) for different wind speeds and different imposed noise constraints. This reduction in power, however, is only significant for wind speeds between 10 m/s and 12 m/s. In figures 10 and 11 we show the values of the optimum rotational speed and the pitch setting that have been utilized to achieve the maximum noise reductions shown in figure

9. As expected, the most important means for reducing noise is lowering the rotational speed, combined, however, with some changes in the pitch angle (usually by pitching away from stall).

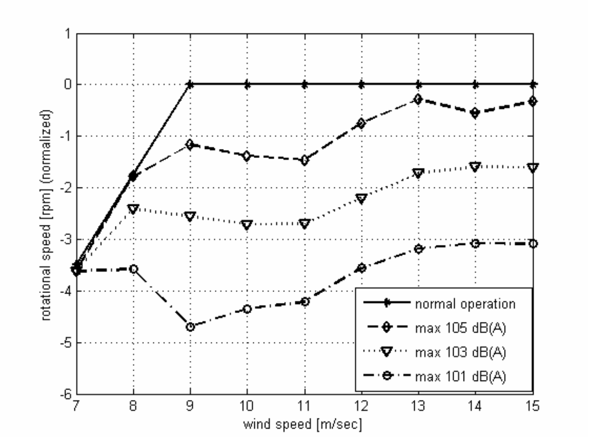

Figure 10: Modifications of the rotational speed leading to the optimum noise constrained power curves.

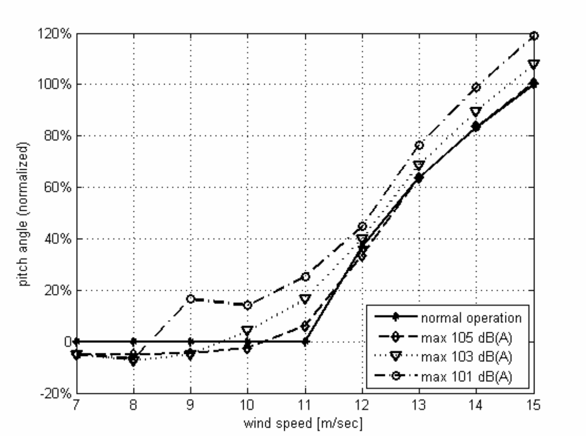

Figure 11: Modifications of the pitch setting leading to the optimum noise constrained power curves.

5. Conclusions

A semi-empirical noise model has been validated by comparing computations with measurements of a Siemens SWT-2.3-93 wind turbine. The measurements were performed using 4 microphones located in the vicinity of the wind turbine that was operated at different rotational velocities and different pitch angles. The comparison shows that the model tends to over predict the noise level at normal operation conditions of the wind turbine, and that it follows the correct trend when varying the pitch setting and the rotational speed of the rotor. The computed noise spectrum is in excellent agreement with the measured one up to frequencies of 3 kHz. For higher frequencies, however, there seems to be a systematic problem in relation to the expression for blunt trailing edge noise. This excess in the right side of the predicted spectrum is also responsible for the overall overprediction.

The code was coupled to an optimization tool and used for optimizing the wind turbine's operational settings. This was done for a series of wind speeds and for two different optimization strategies. It was found that for some wind speeds considerable reductions in noise can be obtained at a low cost. As we approach the wind speed at which the noise level is highest, however, the loss of power increases considerably.

It is our hope that this kind of optimization can lead to a more quiet operation of existing wind turbines by simply varying the tip speed and pitch setting in a an appropriate manner.

Acknowledgements

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