# Noise Optimization of a Siemens Multi-MegaWatt Turbine

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**Abstract**. A method has been developed for the noise optimization of a wind turbine. The main purpose of the method is to identify the most efficient way to reduce the aero-acoustic noise emission from the wind turbine. The secondary purpose is to evaluate the applicability of an engineering code for aero-acoustic noise prediction.

High-quality recordings of the total sound pressure from a Siemens SWT-2.3-93 were carried out over a two-day period, operating the turbine in fixed pattern of systematic changes of rotor speed and pitch angle. The acoustic data were synchronized with the data logging from the turbine control system. As a result thousands of 10s 1/12-octave spectra were recorded and were entered into a database holding blade pitch, rotor speed, nacelle wind, power production and sound power as associated entries.

The database facilitates selection of the optimum modes of operation providing maximum power output when noise control is required.

Furthermore, the database enables verification of a new aero-acoustic code based on models by Amiet (turbulent inflow noise), Brooks, Pope and Marcolini (boundary layer noise, blunt edge noise) and Moriarty. Comparison includes the sound power scalars and the 1/12-octave spectra.

The results indicate that some noise sources are well predicted by the code, others are not. The turbulent boundary layer sources seem well estimated within a few dB. The separated boundary layer source is at least qualitatively well predicted also, while the blunt trailing edge noise is severely over-predicted. Recognizing that the turbulent boundary layer sources dominate in non-stalled operating conditions, it seems likely that the engineering aero-acoustic code can assist in future design of low-noise airfoils.

## 1. Introduction

The importance of wind power is set to increase rapidly over the coming years. As a result more people will receive acoustic impact from wind turbines, so noise concerns are likely to grow. At the same time there are operational benefits associated with an increased blade tip-speed which is known to increase noise. Consequently, there is clear motivation for optimizing the turbine acoustically.

This can be done in two ways:

- Measurement of the sound emission and operational data (wind, pitch, rotor speed, power, etc) for all operating conditions. Then minimize the (lost power)/(reduced noise) ratio by tuning the rotor speed and pitch curves.
- Modeling of the sound emission and operational data, then minimize the (lost power)/(reduced noise) ratio.

Performing the optimization from measured data is the real thing, but ás a designer you are always one iteration behind: You cannot optimize before the blade exists physically, and once it does it is not easy to iterate further on the blade layout (chord-, thickness-, twist- and airfoil-distributions). The model operates on an imaginary blade which can be iterated much easier in any respect. However, validation of such model will be crucial.

Trying to benefit both from real measurements and from the acoustic model we follow the standard procedure: First, obtain a reference by measuring the physics. Then, investigate if measured physics compare well with the model and, if possible, tune the model parameters to improve the fit.

The details of the acoustic measurements are explained in Section 2. The acoustic model is briefly presented in Section 3 followed by the measurement-model comparison. Section 4 explores the possibilities for reduced noise power production. Conclusions and outlooks finalize the paper in Section 5.

## 2. Aero-acoustic noise measurements of an SWT-2.3-93

The Siemens SWT-2.3-93 is a typical modern multi-megawatt wind turbine. Rated power is 2.3MW, and the rotor has three 45m blades with a rotor diameter of 93m. The turbine operates with variable speed up to 16rpm and has pitch control. The test turbine has 80m hub height and is located at Høvsøre National Test Site for large prototype turbines at the west coast of Jutland. The Test Site has five turbines sited in a south-north oriented row, see Fig. 1.

*Figure 1: Aerial view from north of Høvsøre Test Site. The SWT-2.3-93 is fifth in the row (right)*

The measurement campaign took place during two consecutive days in May 2006. The days were sunny, with moderate temperatures of 10-15 degrees Celsius and wind from a constant westerly direction. Wind speeds varied between 4m/s and 13m/s.

During the measurement campaign the normal control system was overridden so rotor speed and blade pitch curves could be controlled manually and varied systematically independently of each other. In total 11 hours of measurements were obtained, including operational turbine conditions and idling conditions in between when the background noise was recorded.

Overall the measuring conditions were fine. High-pitched bird noise contaminated at times, and beyond a certain wind speed the breaking of the waves on the North Sea shore more than 1km away would cause a sudden rise in the background noise level, but both influences could be accounted for in the post processing.

The acoustic noise recording hardware and processing software was manufactured by Brüel & Kjær [1]. The single microphone measuring location was in the centre of a 1m diameter circular board laid flat on ground 100m downwind of the tower base. The turbine operational data (wind, pitch, rotor speed, power, yaw angle, etc) was taken from the turbine control system and plugged into the Brüel & Kjær hardware, synchronizing noise recordings with turbine data. At post-processing the soundtrack was binned into 10s averages and split into 1/12 octave frequency spectra.

The binned sound pressure levels were then adjusted for the flat plate reflection (6dB offset, [2]), A-weighted and converted to sound power levels for the turbine using the normal assumption that turbine noise can be considered as emitting from a point source at the rotor centre.

Results are shown in Figure 2.

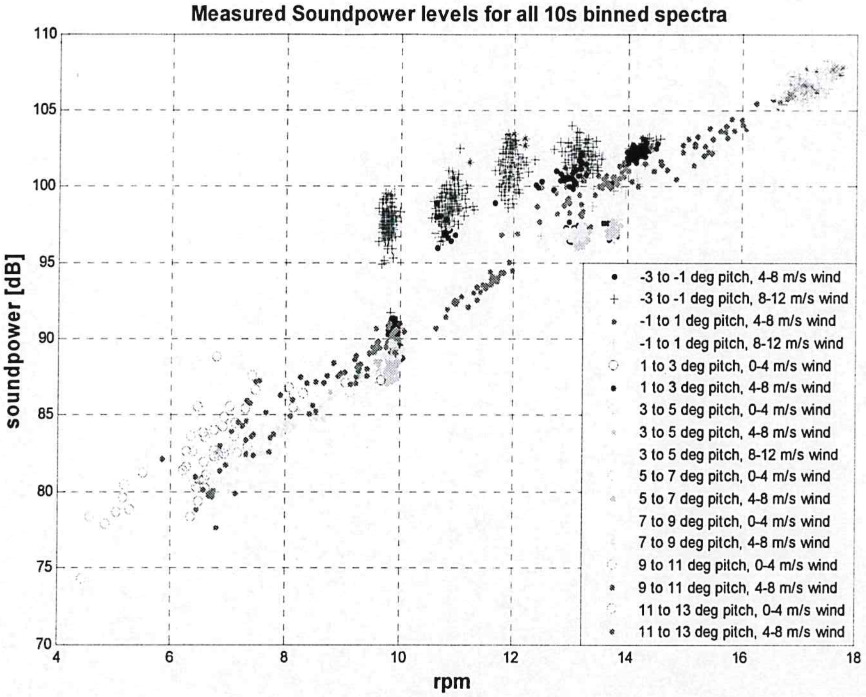

*Figure 2: Measured sound power level plots [dB(a)] for the Høvsøre SWT-2.3-93*

Inspection of Figure 2 gives the immediate impression of points on a straight line and then occasional off-line points. The black and magenta off-line points are for negative blade pitch, so they are related to stalled conditions. Operating blade-pitch is in the range -1 to 1 degrees (magenta points), which is where the flow around the blade starts to exhibit light stall behavior. Below 8 rpm the signal-to-noise ratio of the measurements deteriorated, causing increased scatter in the sound power levels.

For non-stalled operating conditions (positive blade pitch) the A-weighted sound power level for the SWT-2.3-93 can be expressed as a simple function of $v_{tip}$ , the tip-speed

$$\mathrm{SP(a)} = 65.25\mathrm{dB} + 0.498\tfrac{dB\cdot s}{m}\cdot v_{tip} \qquad (1)$$

Consequently, for non-stalled conditions the sound power is largely independent of both blade pitch and wind speed at hub-height. The significant exception is at onset of stall and well developed stall where the sound power increases by between 2dB and 8dB. During stall conditions the wind speed influences the sound power level, as expected. At maximum rotor speed (16rpm) the effect of negative blade pitch diminishes with respect to noise. This is simply because onset of stall is delayed as rotor speed increases.

Although wind speed affects sound power in lightly stalled and stalled conditions, the wind speed dependency on noise is almost negligible outside stall. This tempts us to visualize the data in Fig.2 as contours depending only on rotor speed and pitch. Where wind speed variations impact the sound power (i.e. in stall) the contours are extracted for data at wind speeds around 8m/s, see Fig.3.

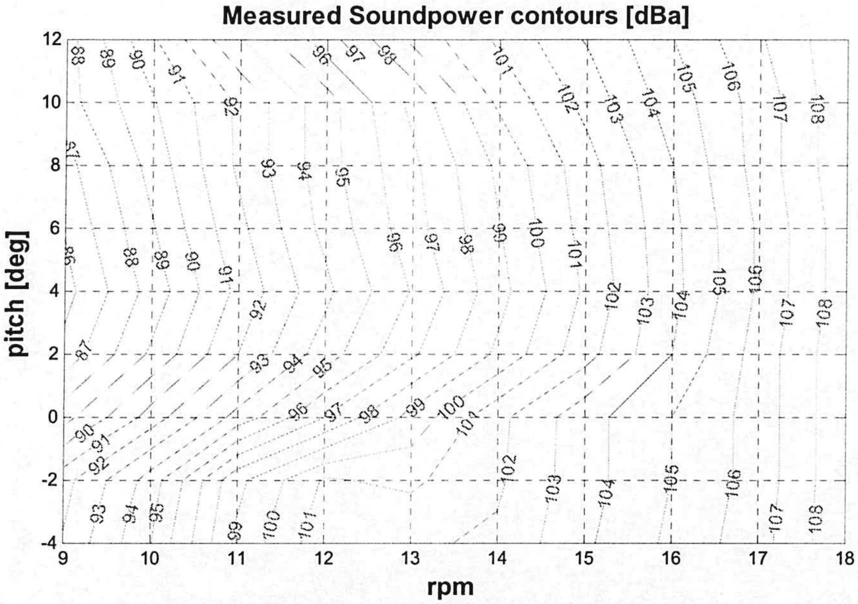

*Figure 3: Measured sound power level contours [dB(a)] for the Høvsøre SWT-2.3-93*

### 3. Aero-acoustic noise calculations of an SWT-2.3-93 and comparison with measurements

The aero-acoustic noise source model is based on the widely referenced experimental work by Brooks, Pope and Marcolini (BPM) [3] who identified distinct types of aero-acoustic noise sources:

- Trailing edge bluntness vortex shedding noise.
- Laminar boundary layer trailing edge vortex shedding noise.
- Turbulent boundary layer trailing edge noise.
- Turbulent boundary layer separation noise.

Another aero-acoustic noise source is turbulent inflow noise. Turbulent inflow noise is generated when blade passage through a turbulent eddy causes cascading into smaller eddies. The model proposed by Amiet [4] is used.

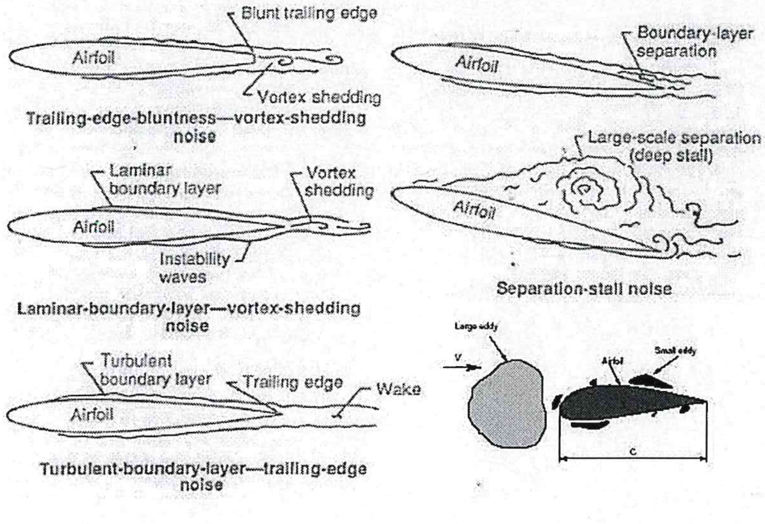

*Figure 4: The 5 aero-acoustic noise sources in the model*

The models by [3] and [4] have been developed further. The BPM model was originally derived from acoustic measurements on the NACA 0012 airfoil using measured boundary layer quantities from another experiment by Schlinker & Amiet [5]. Aiming at airfoil geometry flexibility, the boundary layer quantities can be readily obtained from Drelas Xfoil [6] boundary layer solver. Airfoil geometry impact was also introduced for the turbulent inflow noise model in recent works by Moriarty et al. [7], [8].

The actual acoustic source model implementation is the open-source software NAFNoise by Moriarty [9]. A tailor-made version of Xfoil lies nested inside this code. NAFNoise is used as an engine by the Siemens Wind Power turbine performance in-house code Xblade to populate a database from which acoustic calculations can be efficiently computed along with other relevant turbine data.

The aero-acoustic noise propagation model takes into account the following physical contributions:

- Directivity.
- Distributed source calculation.
- Air absorption.
- Wave refraction due to atmospheric shear.
- Doppler effect.

Absent from the above list is terrain slope – a non-inclined flat terrain is assumed. Multiple ground reflections from the same sound ray are not accounted for either. This phenomenon could come into play at long downwind distance from the turbine due to the stratification of the atmospheric shear layer.

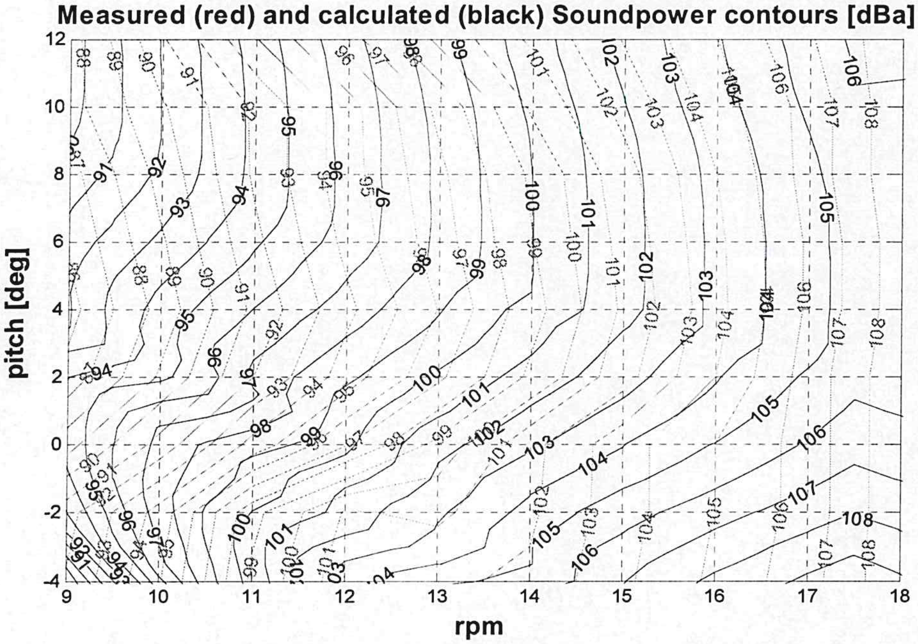

*Figure 5: Calculated sound power level contours [dB(a)] superposed on measured, see Fig.3*

Figure 5 shows the ability of the aero-acoustic model to reproduce the measured data at a wind speed of 8m/s. From a rotor speed of 12rpm and upwards the model fits within a 2dB margin. The exception is in the stall region at high rotor speeds where the model overestimates the separation noise increase for decreasing pitch angles. Apart from this, the rather weak sound power dependency on pitch is well captured by the model. Note also that both measurements and model indicate an acoustically optimal pitch setting of 4-6 degrees for rotor speed above 12 rpm.

The calculated contours were not the first output from the model with default settings; the NAFNoise parameters have been tuned to provide a reasonable fit. The details of these model-to-measurement adjustments are:

- The trailing edge bluntness vortex shedding noise component is over-predicted more than 5dBs by the model, hence it was excluded from the total noise computations.

- For the turbulent boundary layer noise components, the BPM model was used with boundary layer quantities calculated by Xfoil. An alternative model by Moriarty & Migliore [10] is implemented in NAFNoise and was tested. The results in this case were disappointing compared to the BPM model. Neither the absolute sound power level nor the trends (gradients) of the contours came close to the measured reference of Fig.3.
- Although turbulent boundary layer noises (trailing edge and separation) are the main contributors to the total sound spectrum envelope, turbulent inflow is responsible for the lower frequency part of the spectrum, which at times contributes significantly to the overall sound power level. Turbulence levels and the length scale of eddies interacting with the blade must be considered.
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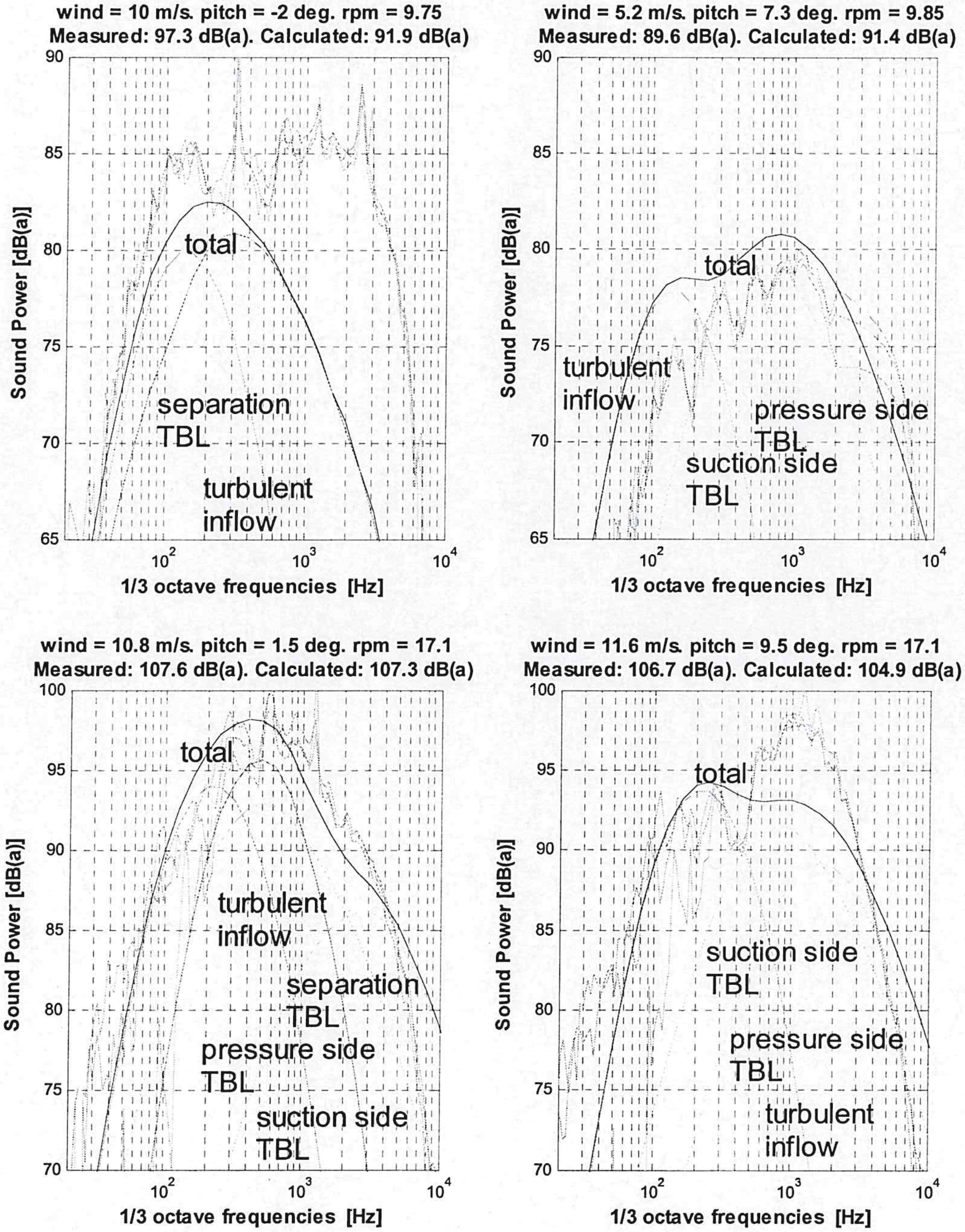

wind = 10 m/s. pitch = -2 deg. rpm = 9.75
Measured: 97.3 dB(a). Calculated: 91.9 dB(a)

wind = 5.2 m/s. pitch = 7.3 deg. rpm = 9.85
Measured: 89.6 dB(a). Calculated: 91.4 dB(a)

wind = 10.8 m/s. pitch = 1.5 deg. rpm = 17.1
Measured: 107.6 dB(a). Calculated: 107.3 dB(a)

wind = 11.6 m/s. pitch = 9.5 deg. rpm = 17.1
Measured: 106.7 dB(a). Calculated: 104.9 dB(a)

*Figure 6: Measured and calculated spectra at 4 different operation points*

The sound power level is the primary scalar concerning aero-acoustics and the obvious choice for comparison. It is an accumulated quantity found by adding the individual source types and integrating over the frequency spectrum (either 1/3-octaves or 1/12-octaves). A nice fit on the sound power level indicates that the model is suitable, but a more detailed comparison is obtained by comparing the spectra. Figure 6 shows calculated (individual noise types + total) and measured spectra at four very different operational points of the turbine, where a number of 10s bins had almost identical wind-pitch-rpm settings of the turbine:

- Low pitch, low rotor speed: Stall region. Turbulent boundary layer separation and turbulent inflow noise dominate. The high background noise (breaking waves) caused a low signal-to-noise ratio, which is probably part of the explanation for the poor fit.
- High pitch, low rotor speed: No-stall region. Turbulent boundary layer trailing edge noise and turbulent inflow noise dominate. Good fit, even though the turbulent inflow noise seems over-predicted by the model.
- Low pitch, high rotor speed: approaching stall region. Turbulent boundary layer separation and turbulent inflow noise dominate. Excellent fit.
- High pitch, high rotor speed: No-stall region. Turbulent inflow noise dominates in model. Measurement indicates that the turbulent boundary layer trailing edge noise is actually the dominating source. Nice overall fit, especially for the turbulent inflow noise.

## 4. Options for low-noise power production

Once the blade is manufactured, there are only 2 handles for noise-reduction: Blade pitch and rotor speed. As shown in Figure 7, every low-noise operation comes with a price. At 8m/s the operational setpoint that yields maximum power output is at -1deg pitch and 14.9 rpm. Pitching out from here (positive direction) aiming at a 1dB reduction will cost in the order of 3% power. On the other hand, reducing rotor speed until 1dB reduction is reached would cost a minimum of just 0.3% power.

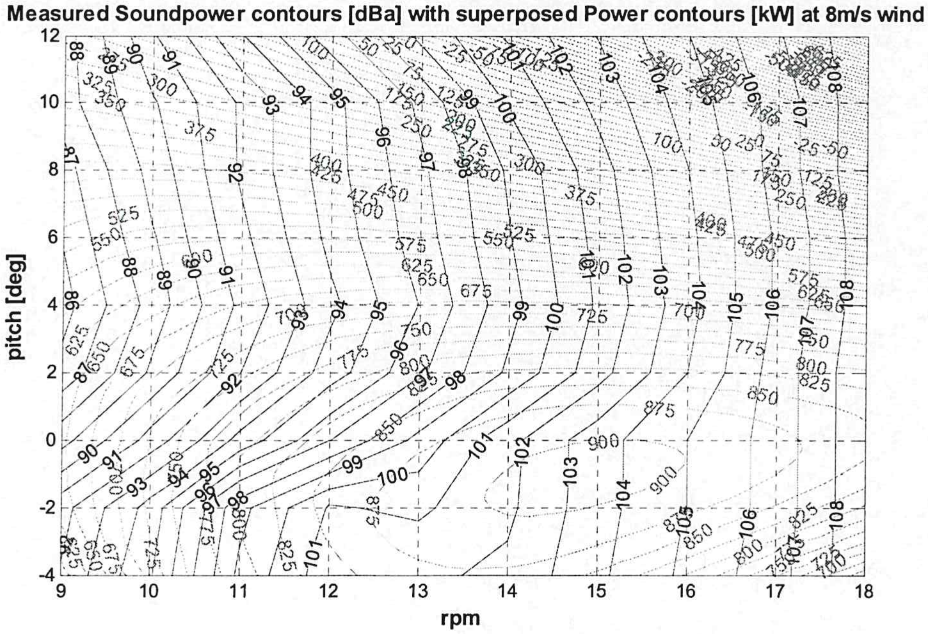

*Figure 7: Measured sound power level contours [dB(a)] with elec.power contours [kW] superposed.*

The aero-acoustic model has been used for the analysis below. It has been tuned to within a reasonable accuracy and will provide sound-power gradients in all directions (wind, rotor speed, pitch).

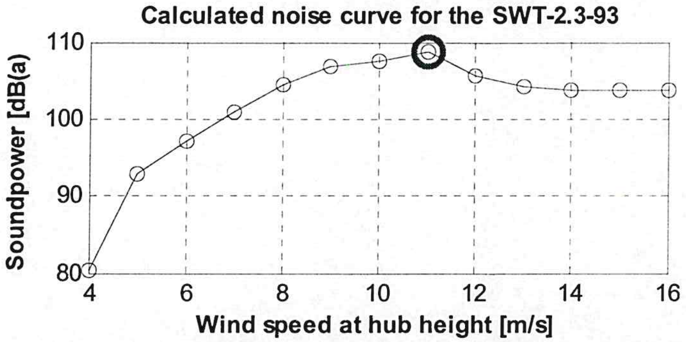

*Figure 8: Calculated wind-sound power relation for optimal pitch/rotor speed settings (production curve).*

Figure shows that the maximum sound power level occurs at 11m/s. The reason for the noise decline with further increasing wind is that rated power has been reached, and the blades will pitch out away from stall. Hence, low-noise power production must focus on the 11m/s operating conditions.

The obvious benefit of an aero-acoustic model is that it can operate on imaginary blades and provide basis for a very specific blade optimization, beyond the scope of this brief introduction. A very basic gradient analysis for simple operating and geometric variations of the existing 45m blade SWT-2.3-103 is presented in Table 1. All data has been calculated with the in-house turbine performance code into which the aero-acoustic code has been implemented. The noise values refer as always to the A-weighted sound-power. AEP is the annual power production. The flapwise load parameter is the estimate of the Weibull-weighted fatigue-moment of the blade root from flapwise blade dynamics.

| **Parameter variation** | **Noise gradient [dB / change]** | **AEP gradient [% / dB]** | **Flapwise gradient [% / dB]** |
|---|---|---|---|
| Blade pitch [deg] | -1.05 dB/deg | -0.2 | 0 .0 |
| Rotor speed [rpm] | 0.72 dB/rpm | -0.5 | -1.5 |
| Blade chord [%] | -0.03 dB/(%chord) | 2.5 | 28 |
| Blade thickness [%] | -0.02 dB/(%thickness) | -8.4 | 4.5 |

*Table 1: Calculated gradient analysis for SWT-2.3-103.*

Table 1 shows that dB-reduction can be achieved by blade pitching with minimum AEP sacrifice and without increasing flaploads. However, it should be noted that the aero-acoustic model over-predicts the noise sensitivity to pitch-variations when compared with measurements (Figure 5, high rotor speed and negative pitch).

Reducing rotor speed at 11m/s costs 0.5% power per reduced dB, and comes with a reduced load benefit.

Increasing chord will actually lower the noise level and yield higher AEP, but the price paid in load-increase is substantial. Thicker blades also tend to lower the noise, but AEP drops and loads increase.

## 5. Conclusions and future work

Conclusions regarding aero-acoustic model validation:

- The model of trailing edge bluntness noise over-predicts measurements by 5+ dB. Consequently, bluntness noise is not included in any of the calculations presented here.
- Turbulent boundary layer separation noise is qualitatively well reproduced by model, but the magnitude is over-predicted. Rotational 3D-effects that postpone stall might explain part of the discrepancy.
- Turbulent boundary layer trailing edge noise model fits measurements well.
- Turbulent inflow noise model generally fits well at low frequencies, where it is the dominating noise source, and the magnitude is comparable to measurements.
- Overall the model can deliver accurate predictions once the deficiencies (bluntness) and weaknesses (separation noise) are identified.

Conclusions regarding low-noise turbine operation potentials

- Positive pitching (away from stall) is the primary handle according to model – however, measurements indicate much less pitch sensitivity. Reduced rotor speed also reduces noise at a low cost according to both model and measurements.
- Chord- and thickness-variations do not show significant impact on acoustics, and AEP- and/or load-cost is significant.
- Every dB-favourable change has a cost, either on AEP or loads.

Suggestions for future work

- Identify reasons for trailing edge bluntness model inadequacy (manufactured trailing edge smoothing ?).
- Include rotational effects in XFoil (RFoil ?) and analyse its impact on separation noise.

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