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Published in:
Proceedings. 6th International Meeting on Wind Turbine Noise

Publication date:
2015

Document Version
Peer reviewed version

6th International Meeting
on
Wind Turbine Noise
Glasgow 20-23 April 2015

Development of a high-fidelity noise prediction and propagation model for noise generated from wind turbines

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Abstract
An approach to combine the actuator line technique with the improved Brooks, Pope, and Marcolini (IBPM) model for wind turbine noise calculation is presented. The IBPM needs Mach number, local angle of attack and blade position as an input. These can be calculated accurately with the actuator line technique for any kind of flow conditions. We investigated laminar/ turbulent inflow, as well as wind shear and yaw of the 2.3 MW NM80 wind turbine. The turbulent case shows higher noise levels than the laminar one. Yaw changes the directivity from a dipole characteristic to an oval shape, inclined by the yaw angle.

1. Introduction
Aeroacoustic noise from wind turbines is an issue of growing importance. The pace of growth of on-shore wind energy has led to turbines being placed closer to where people live. Placing the turbines close to residential areas creates acceptance problems, especially in densely populated areas such as Europe. Consequently noise regulations have become stricter, particularly in Denmark.
In the past the most dominant noise was generated by the mechanical components of wind turbines. Due to well manufactured wind turbines this noise level could be lowered, so that the most dominant noise of modern wind turbines is due to aerodynamic interactions of the blades with the incoming flow.
Aerodynamic noise can be divided in two major mechanisms. Turbulent inflow noise appears due to the interaction of the rotor blades with atmospheric turbulence. Airfoil self-noise is generated by the interaction of locally undisturbed flow with the airfoil.
For both mechanisms semi empirical formulations have been published by fitting experiments to acoustic analogies. In this paper we use the improved Brooks, Pope, and Marcolini model (IBPM) (Zhu et al. 2005) to calculate the wind turbine noise. Turbulent inflow noise is calculated according to Lowson (Lowson 1993). The airfoil self-noise calculation is based on the model of Brooks, Pope and Marcolini (Brooks et al. 1989).

Both models need geometrical data of wind turbines, such as airfoil orientation and shape, which are known in advance. On the other hand they also need aerodynamic properties, such as local angle of attack and relative velocity at the blade.
Due to the increasing computational power, highly accurate aerodynamic computations of wind turbines are becoming more and more popular.
In the present work Large Eddy Simulations (LES) with the actuator line technique are used to obtain the needed aerodynamic properties. With this method wind turbines in wind shear, yaw, atmospheric turbulence and wake conditions can be simulated.
The paper is organized as follows. In section 2, the methodology of the actuator line technique, the used IBPM model and adding atmospheric turbulence is described. In section 3 the results are presented and discussed. Section 4 contains the conclusion.

2. Methodology

Our approach to calculate noise of wind turbines is to use the actuator line technique (Sørensen Shen 2005) combined with the improved Brooks, Pope and Marcolini model. With the actuator line technique we get the time dependent, fluctuating flow field around a wind turbine. We can model different kinds of flow conditions, such as wind shear, yaw, and atmospheric turbulence. Important parameters are extracted from the actuator line calculation and used as an input of the IBPM model.

2.1 Actuator line technique

First we calculate the fluctuating incompressible flow field around a wind turbine with the Actuator Line Model and Large Eddy Simulation (LES). This is done with the block structured, multigrid FVM solver EllipSys3D, developed at the Technical University of Denmark (Michelsen 1992) in cooperation with the Department of Wind Energy at Risø National Laboratory (Sørensen 1995).

Forces are added to the flow computation along lines, representing the moving blades of a wind turbine,

$$\frac{\partial U_i}{\partial t} + \frac{\partial (U_i U_j)}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j^2} + \boldsymbol{f_i},$$

$$\frac{\partial U_i}{\partial x_i} = 0,$$

$$\boldsymbol{f} = \frac{1}{2}\rho U^2 c(C_L, C_D),$$

with U_i as velocity, P as incompressible pressure, ρ_0 as density, ν as kinematic viscosity and $\boldsymbol{f}$ as the added body forces. The body forces are calculated out of airfoil data.

Out of the actuator line technique we get the fluctuating, relative flow velocity, position of the blade, and the current angle of attack at the blades. These values are used to calculate the noise emission of the wind turbine with the IBPM model.

2.2 Improved Brooks, Pope, Marcolini model

The IBPM model is a semi empirical acoustic generation model. Two different noise mechanisms are taken into account. Both are based on semi empirical equations of sound pressure levels for airfoils. Turbulent inflow noise is predicted with the model by Lowson (Lowson 1993). Airfoil self-noise is predicted with the Brooks, Pope, and Marcolini model (BPM) (Brooks et al. 1989).
In the IBPM model each blade is subdivided into blade sections. For each blade section the sound pressure level is calculated. Afterwards the sound pressure level of each blade section is summed up and A-weighted to get the A-weighted sound pressure level at a specified observer position.

Exemplarily the sound pressure level equation for Turbulent Boundary Layer Trailing Edge noise of the suction side is given by

$$SPL_{TBLTE} = 10\log_{10}\left(\frac{\delta_s^* M^5 \Delta l D_h}{r^2}\right) + G_A\left(\frac{St_s}{St_l}\right) + (W_1 - 3)$$

The important parameters used by the IBPM model from the actuator line calculation are the relative Mach number *M*, the distance between the current blade section location and the observer point r, and the boundary layer displacement thickness δ_s^*, which is dependent on the angle of attack, Reynolds number and airfoil geometry. For further details we refer to the paper by Zhu (Zhu et al. 2005).

2.3 Atmospheric Turbulence

To add turbulent inflow, we use the so called the Mann model (Mann 1994). Like in the actuator line technique, small forces are added to perturb the flow. These forces are computed with respect to the Mann model and saved as slices in a turbulent box. At specific time steps a slice of the turbulent box is added to the flow field in front of the rotor. The added forces generate a turbulent flow field, modelling atmospheric turbulence.

3.0 Results and Discussion

3.1 Calculation layout

Within this paper we show the results of four different calculations. They are summarized in Table 1. All calculations are done for a NM80 wind turbine with a blade radius of 40m and a rated power of 2.3MW.

	Wall	Wind shear	Yaw	Turbulence	Wind speed	Tip speed
a)	x	x	x	x	8.5 [m/s]	72 [m/s]
b)	x	x	x	✓	8.5 [m/s]	72 [m/s]
c)	✓	✓	x	x	8.0 [m/s]	72 [m/s]
d)	✓	✓	✓	x	8.0 [m/s]	72 [m/s]

Table 1: Calculation scheme

For the first calculation a), the wind turbine is placed in a free stream of 8.5m/s. This calculation is used as a baseline to study the influence of wind shear, yaw, and turbulence on sound emission. Atmospheric turbulence is added in the second calculation b). The third calculation c) is done with a ground and the following wind shear profile is added,

$$w = v_0 \frac{y}{H}^{\alpha},$$

with v_0 as a wind speed of 8m/s at 10m height and a shear exponend α of 0.1. In the last calculation d), a yaw angle of 15 degrees is added. The hub height is 60m.

3.2 Angle of attack and relative velocity

First we show in Figure 1 the change of the local angle of attack on blade 1. This data is extracted from the actuator line computation and is used as an input for the IBPM model.

The local angle of attack and relative velocity are changed at the blade location due to the applied forces out of the actuator line technique.

It can be seen that the local angle of attack at a blade section at 80% of the radius is almost constant for calculation a). With added atmospheric turbulence in front of the rotor the local angle of attack fluctuates strongly around the local angle of attack of calculation a). The difference in angle of attack is up to 3.6°.
Calculations with wind shear show an expected, periodic change in angle of attack. At the top position of the blade the angle of attack is highest and decreases as the blade moves

downwards to lower inflow wind speeds. The change in angle of attack is 1.1° without yaw and increases due to yaw to 2°. Also the maximum and minimum angles of attack are higher and lower with yaw, respectively.

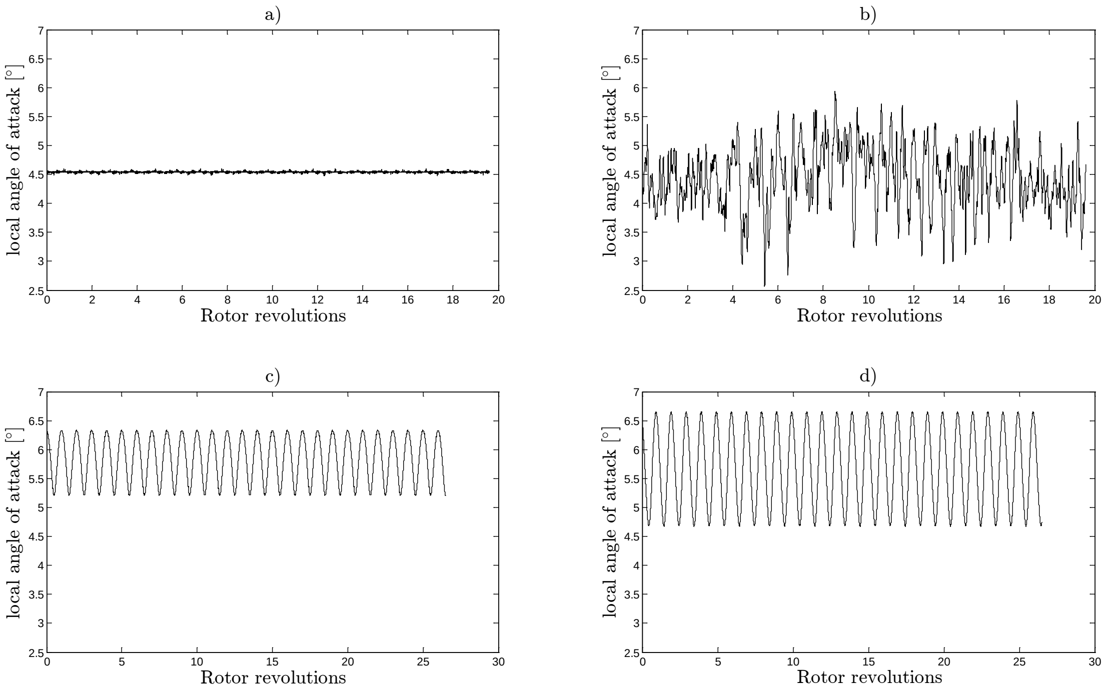

Figure 1: Local angle of attack over rotor revolutions of blade 1 at 80% of the radius

The second input from the actuator line calculation to the IBPM model is the relative velocity and hence Mach number at each blade section. This is illustrated in Figure 3. It shows the same behaviour as the angle of attack.
Due to the changes in angle of attack and local Mach number, the sound pressure level varies either periodically for wind shear cases, or chaotically due to turbulence.
To illustrate the effect of the added turbulence, the flow field at a top view at hub height of the wind turbine is shown for case a) and b).

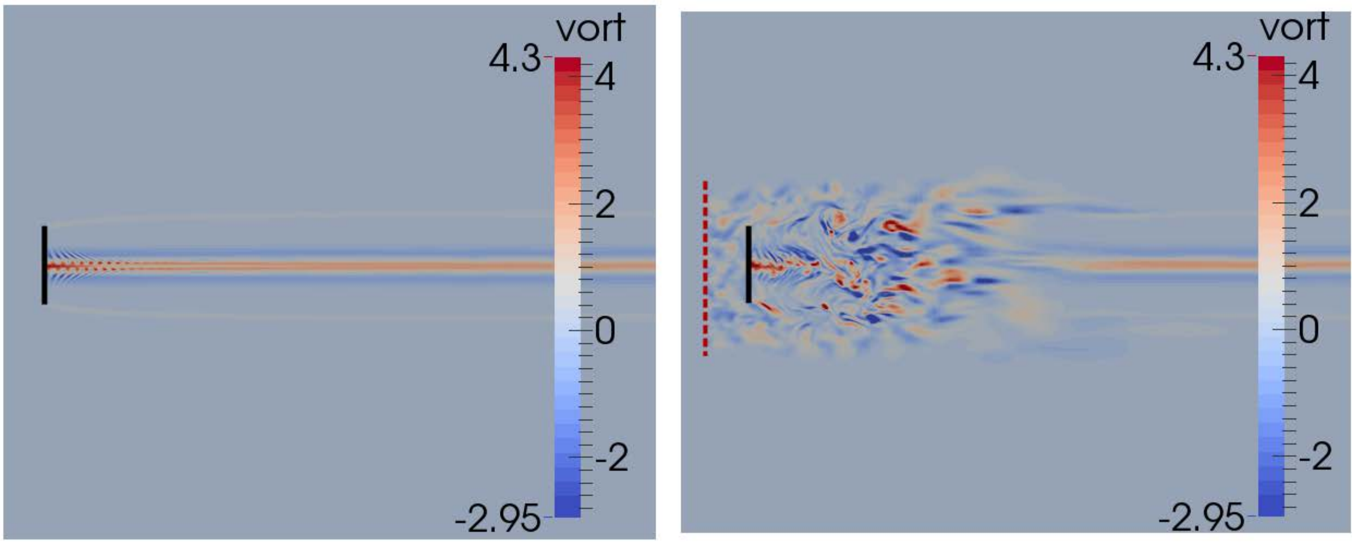

Figure 2: Vorticity from top view at hub height, left a), right b)

On the left, the vorticity field generated by the wind turbine can be seen for calculation a), on the right the one corresponding to calculation b). The flow is from left to right and the turbine is placed at the black line. In calculation a) the distinct tip and root vortices can be seen due to the laminar inflow. In calculation b) a turbulent box is placed at the red line,1R in front of the rotor. Vorticity is fluctuating at the inflow of the turbine and consequently angle of attack and velocities at the blade.

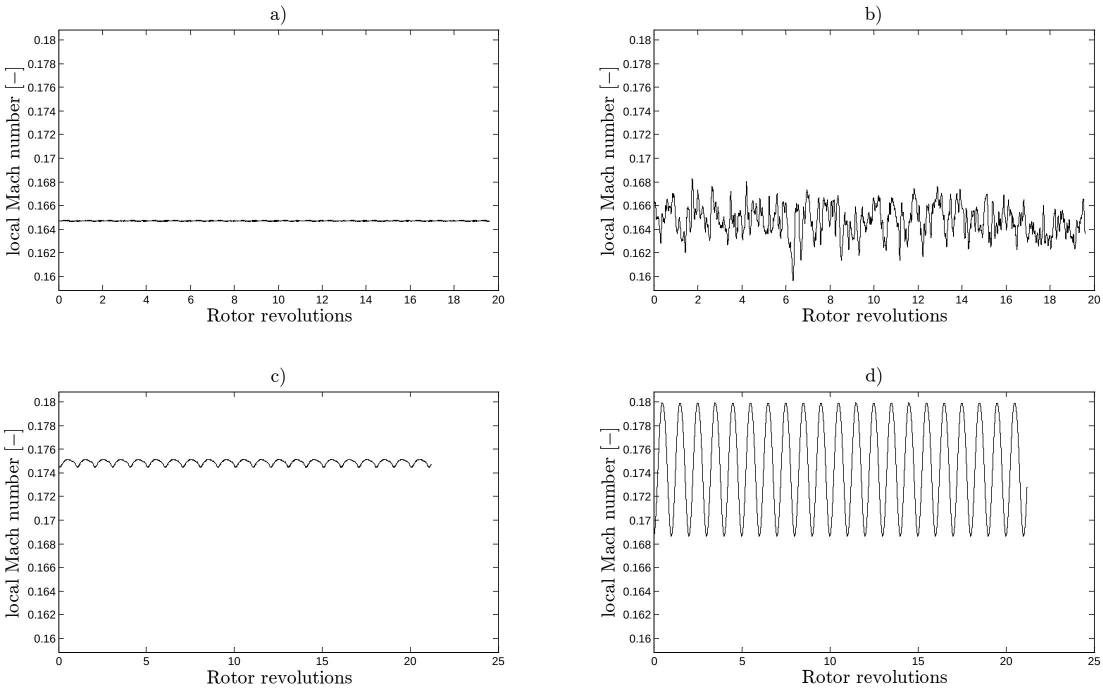

Figure 3: local Mach number of blade 1 at 80% of the radius

3.3 Directivity

In Figure 4, we show directivities at a distance of 80m. The maximum A-weighted sound pressure levels (SPL) is shown for calculation a), the average over all time steps for calculation b)-d). Each calculation consists of 10000 time steps. A directivity angle of 0° corresponds to a position behind the turbine, an angle of 180° to a position in front of the turbine. The total SPL is the sum of all noise mechanisms of all blade sections of the turbine.

It can be seen that turbulence increases the SPL. The average value is higher for calculation b) than the maximum SPL value of calculation a).

For the wind shear cases c) and d) it is observed that pure wind shear does not change the directivity in this plane. Yaw has a huge influence on the directivity. The dipole characteristic of the directivity is lost and changed into an oval like shape, shifted by the yaw angle of 15°.

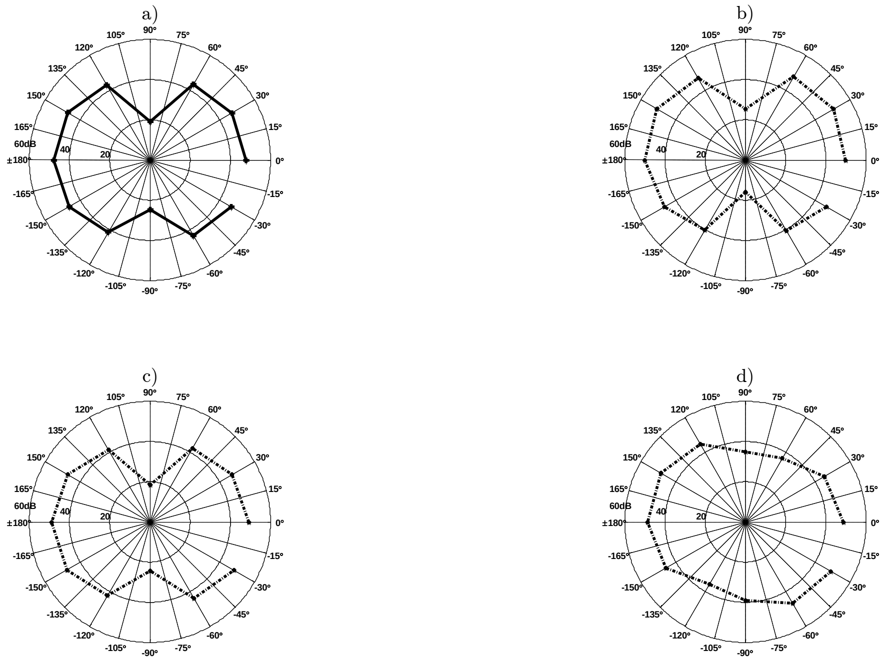

Figure 4: Directivities of A-weighted sound pressure levels at 80m distance

3.4 Sound power level

Out of the IBPM model we also get the A-weighted sound power levels for the 1/3 octave band. In the following figure the averaged sound power levels are shown.

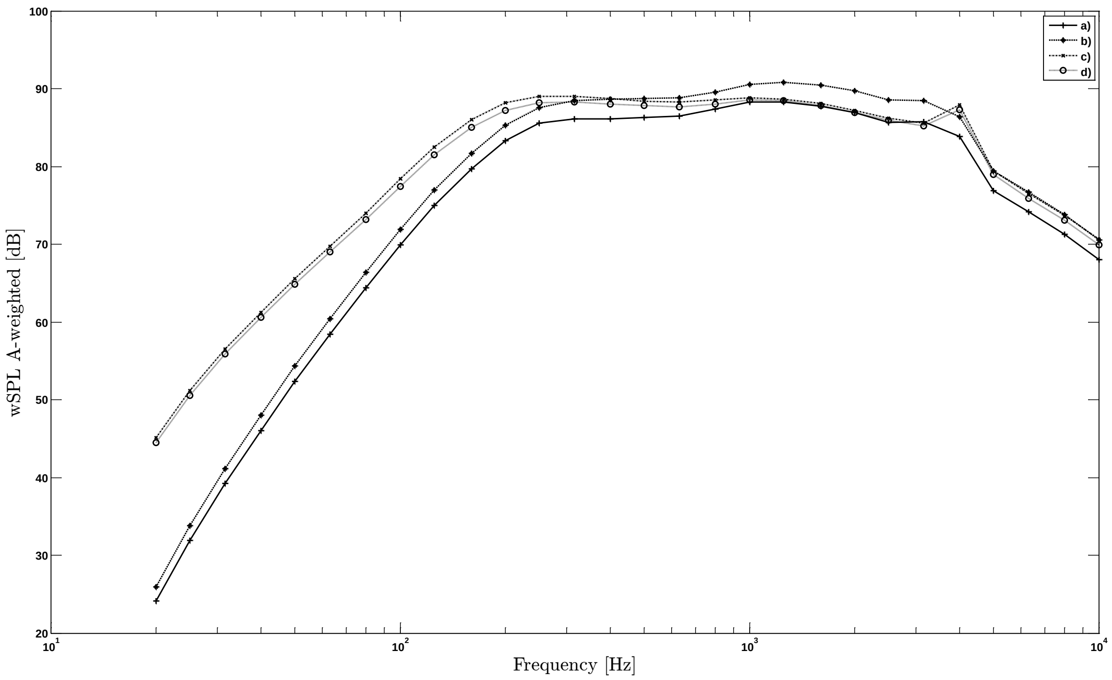

Figure 5: A-weighted sound power level in 1/3 octave band

The sound power level is higher at lower frequencies for calculations with wind shear. In these calculations the wind speed is set to 8m/s at 10m height, hence at hub height the wind speed is higher than in cases a) and b). Due to the higher wind speed, the angle of attack is higher. At higher angles of attack the boundary layer thickness is larger which leads to a higher noise level at lower frequencies.

4.0 Conclusions

We developed a method to use the actuator line method combined with the IBPM model. With the actuator line technique any flow condition can be simulated and used as an input for the IBPM model. In this paper we showed results for noise calculations with laminar and turbulent inflow, wind shear and yaw. The time dependent change of angle of attack and Mach number are shown, as well as directivities for different flow conditions.
In future work the calculations can be done for a turbine with wind shear and turbulence, as well as noise emission of a turbine in wake conditions.

Acknowledgement

This work is supported by the EUROTECH Wind project which is the collaboration between Technical University of Denmark, Technische Universität München, Eindhoven University of Technology, École Polytechnique Fédérale de Lausanne.

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