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Wind turbine noise generation and propagation modeling at DTU Wind Energy: A review

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ABSTRACT

The present review paper provides a comprehensive overview of the research activities on wind turbine aeroacoustics at DTU over the last 20 years, as well as it gives the state-of-the-art of noise prediction models for wind turbines under complex inflow conditions. Various noise generation models developed at DTU are described and analyzed, including models based on the acoustic analogy, flow-acoustics splitting techniques, Amiet's model, and various engineering models. Some of the models are coupled to existing aero-elastic software and computational fluid mechanics models developed at DTU, and implemented in the simulation platform WindSTAR (Wind turbine Simulation Tool for AeRodynamic noise). This simulation platform consists of WindSTAR-Gen, dealing with models for generation of noise and design of low-noise wind turbines, and WindSTAR-Pro, which is developed to handle the modeling of long distance acoustic propagation. As specific features of the WindSTAR-Pro package, the rotation of the noise sources is modeled, the propagation simulations combine the so-called Parabolic Equations (PE) propagation model with numerical flow simulations to take into account effects from wind turbine wakes, atmospheric turbulence and wind shear.

1. Introduction

The recent Paris agreement requires national climate panels to limit the global temperature increase below 1.5 °C, which is a quite challenging task for many countries. Denmark, which is the country with the largest penetration of wind power, had already more than 40% wind power in the electric grid in 2016, and is heading towards 50% by 2020. Due to the vast increase in rotor size and in the number of wind farms, more environmental impact is expected to occur in the future. The newly updated Danish wind turbine noise regulation [1] is very restrictive for both broadband and low frequency wind turbine noise radiation, which in practice may limit the number of new wind farms on land. Unfortunately, energy yield and noise generation are usually two competing factors. Hence, there is an urgent need to develop sophisticated design tools to fulfil the requirements of high power performance and low noise emission in the design of wind turbines and wind farms.

Noise generation from single wind turbines as well as wind farms has its basis in the nature of aerodynamics, caused by the interaction between the incoming turbulent flow and the wind turbine blades. Hence, understanding the mechanisms of airfoil noise generation, demands access to sophisticated numerical tools. The development in High-Performance Computing (HPC) technology provides many possibilities to perform Computational Fluid Dynamics (CFD) and Computational Aero-Acoustics (CAA) simulations of noise generated from rotor blades.

Among the CAA methods, the most accurate way of simulating aerodynamically generated noise is Direct Numerical Simulations (DNS) where both fluid flow and sound are obtained directly by solving the compressible Navier-Stokes (NS) equations. However, due to the high computational costs of using DNS, the acoustic analogy and different hybrid methods are normally used in practice. The acoustic analogy, proposed by Lighthill [2] in the fifties of the last century, is a well-known CAA approach. To generalize the approach, Curle [3] extended the theory by including the influence of static boundaries. Later on, Ffowcs Williams et al. [4,5] extended the theory further by taking into account the influence of moving solid boundaries. The most recent formulations by Farassat et al. [6,7] are well-validated for helicopter rotor noise predictions.

One of the hybrid CAA methods, proposed by Hardin and Pope [8], is based on a flow acoustic splitting technique. Shen and Sørensen [9] improved the theory of Hardin and Pope by changing the basic decomposition of the variables. Some later modifications of the original splitting method are due to Seo and Moon [10] and Ewert and Schröder

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Nomenclature

AL	Actuator line
AD	Actuator disc
BEM	Blade element momentum
BPM	Name of the wind turbine noise generation model
BPM-CAA-FLEX	Name of the extended wind turbine noise model
CAA	Computational aeroacoustics
CFD	Computational fluid dynamics
CFL	Courant–Friedrichs–Lewy
CNPE	The Crank-Nicholson parabolic equation
DNS	Direct numerical simulation
DTU	Technical University of Denmark
DTU-LN118	The DTU's Low noise airfoil with 18% relative thickness
DRP	Dispersion relation preserving
EllipSys3D	The DTU in-house flow solver
FFP	The fast field program
FFT	Fast Fourier transform
FLEX5	The DTU Wind turbine aeroelastic code 5th version
FW-H	The Ffowcs-Williams Hawkings's acoustic analogy
GTPE	Generalized terrain parabolic equation
GFPE	The Greens function parabolic equation method
HAWC2	The DTU's horizontal axis wind turbine simulation code 2nd version
HPC	High performance computing
LES	Large eddy simulation
LEE	Linearized Euler equation
MPI	Message passing interface
MW-WAPE	Mean-wind wide angle parabolic equation
NREL	National renewable energy laboratory
NS	Navier-Stokes
PE	Parabolic equation
RANS	Reynolds averaged Navier-Stokes
SGS	Sub-grid-scale
SPL	Sound pressure level
TE	Trailing edge
TI	Turbulence intensity
TNO	The noise model named by the organization TNO in Netherlands
TW-WAPE	Turbulent-wind wide angle parabolic equation
WAPE	Wide angle parabolic equation
WAsP	The DTU's wind energy industry-standard software
WindSTAR-Gen	Wind turbine simulation tool for aerodynamic noise-Generation
WindSTAR-Pro	Wind turbine simulation tool for aerodynamic noise-Propagation

[11], with the aim of reducing the growth of hydrodynamic instabilities. The work carried out by Shen et al. [12–15] was based on the second order time and space discretizations, with the acoustic equations derived directly from the original compressible NS equations. The spitting method was developed further by Zhu et al. [16,17] by implementing high-order low-dispersion schemes [18] to the acoustic equations. In a similar formulation proposed by Bailly and Bogey [19–21], referred to as the Linearized Euler Equations (LEE), the velocity source terms are obtained directly from the compressible NS equations.

Even with today's computer resources, the NS-based CFD and CAA methods are still time consuming for rotor design purposes. Simplified approaches are apparently needed for industrial use in the initial design stage. Based on the general theories, many models were developed from the 1970s to the 1990s. Common for these models is that they consist of different semi-empirical expressions that are derived from the acoustic analogy and fitted to some measured data. In the 1970s, an airfoil turbulent inflow noise model and a trailing edge (TE) noise model were proposed by Amiet [22,23], where the homogeneous turbulent inflow and boundary layer turbulent flow are expressed with sinusoidal wave components and modeled by the von Kármán spectrum, respectively. In parallel with the wind energy development in the 1980s, several other prediction models were proposed [24–29]. Brooks et al. [30] formulated a detailed airfoil self-noise model, which consists of scaling laws for five different aerodynamic noise mechanisms. The airfoil noise model is used in wind turbine rotor noise predictions at DTU [31–33] and NREL [34] where the airfoil self-noise is calculated at each rotor blade segment, the local inflow velocity and angle of attack are obtained from the blade element momentum (BEM) method. In addition to the airfoil self-noise, Lawson's rotor inflow noise model [29] is applied, which takes into account the rotational effects from the inflow noise model of Amiet [22]. The inflow noise basically covers a low frequency noise band in the range 10–160 Hz. Madsen [35] proposed a model that takes into account noise generations at even lower frequencies, which is based on the mechanism of unsteady flows over a wind turbine tower. High frequency noise is often as the result of blade trailing edge noise. The noise mechanism is observed in surface pressure measurements near the TE [36–38] of a wind turbine blade at the DTU test site. At a frequency over 2 kHz, wind turbine noise is normally at a rather low level except for two cases: mechanical noise and trailing edge blunt noise. Mechanical noise originates from the gearbox and bearing systems and has been significantly reduced due to technology development over the last decades. A TE creates tonal noise at a relatively high level. The study of Zhu et al. [33] revealed that blunt TE noise can be reduced to a level well below the overall noise level. The text book of Wagner et al. [39] gives an excellent survey of the different types of noise prediction models for wind turbines. With the available wind turbine noise generation models, noise source reductions have been an important task for aero-acoustic experts. Lutz et al. [40] and Wolf et al. [41] demonstrated that active flow control, such as wall suction, can have a positive effect on the TE noise by controlling the boundary layer thickness along the TE. Some passive flow control devices at the TE are more practical. Passive devices at the TE can be either TE brushes [42–44], TE serrations [45–50], porous TE [51], or even porous TE serrations [52]. The TE serration technique has already been applied for large blades in production by wind turbine and blade manufactories such as Siemens, Gamesa and LM Wind Power. This is discussed more detail in Section 3, where a numerical study of an in-house designed low noise airfoil with TE serration will be presented.

Unluckily, it is not straightforward to move from single wind turbine noise generation to wind farm noise propagation modeling, especially for wind farms built in complex terrain. The ambient turbulence level, terrain geometry, wake interaction between turbines and ground can easily change the noise level and the propagation path over a long distance. Similar to wind resource predictions for wind farm planning, noise evaluations for wind farms should be performed before the wind farm is built, such that inappropriate land-use planning can be avoided. So far, the lack of accurate noise predictions for wind farms becomes challenging for social acceptance of wind power [53]. Social acceptance of wind farms is likely to become one of the most important obstacles for a further development of on-land wind power, as can be seen from studies carried in e.g. Australia [54], Greece [55], France [56], Mexico [57], and many other countries. The studies showed that there is clearly a need to develop advanced wind turbine noise prediction tools to treat these problems in advance. Such a tool should include a wind turbine noise generation model and a long distance propagation model. In most of the previous wind turbine noise propagation studies [58–64], a flat terrain with relatively simplified atmospheric conditions is considered.