Research status on aero-acoustic noise from wind turbine blades

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Abstract. This paper describes the noise mechanisms and categories of modern large wind turbine and main noise sources. Then the latest progresses in wind turbine noise researches are described from three aspects: noise prediction model, detection of noise sources by microphone array technique and methods for noise reduction. Although the turbine is restricted to horizontal axis wind turbines, the noise prediction model and reduction methods also can be applied to other turbines when the noise mechanisms are similar. Microphone array technique can be applied to locate any kind of noise sources.

1. Introduction

Wind turbine noise has been regarded to have a character that makes it far more annoying and stressful than other industrial noise or transportation noise at the same A-weighted sound level because it is impossible to insulate it from receivers by acoustic barrier [1-3]. More and more wind turbines are installed on-land and close to dwellings. It makes the proportion of people who complaint of wind turbine noise increases. The noise constitutes an important hindrance for widespread application of
wind turbines. Measured sound power levels for a sampling of wind turbines are presented in figure 1 as a function of rated electrical power. The data illustrate that sound emissions from wind turbines generally increases with turbine size. The graph also shows that the efforts of wind turbine designer in the 1990’s have resulted in significantly quieter wind turbines than the initial designs of the 1980’s. This paper reviews the progresses of researches for wind turbine noise in recent ten years. Some interesting phenomena of noise sources in rotor plane are represented. The effects of serrated trailing edge blades and noise-optimized airfoils are shown.

2. Wind turbine noise sources mechanisms and categories

The noise sources of a wind turbine can be grouped in two main classes, aero-acoustic and mechanical noise [5]. The aero-acoustic noise is the noise generated by rotating blade interacted with wind. The mechanical noise means noise radiated from the tower nacelle. Some aero-acoustic noises generated by the auxiliary equipments of nacelle, such as fan, inlets, outlets and ducts, are usually considered as mechanical noise in wind turbine noise [6].

The different sources of mechanical noise and their transmission path are presented in figure 2. a/b means air borne and s/b means structural borne. Mechanical noise can be suppressed by laying some sound absorbing materials around interior surface of nacelle, so it is always thought to be lesser important and researches about it is very little nowadays. It still can be perceived from some wind turbines [7-8]. The tonal characteristic of mechanical noise makes it annoying and may exceed noise regulation limits, and the low-frequency characteristic of hub noise makes it travelling more far than high-frequency [9]. Certain attention should be paid to mechanical noise when noise reduction should be performed for specific wind turbine.

Aero-acoustic noise from blade is considered to be the main noise source for modern large wind turbines [5]. The aero-acoustic noise radiates from the outer part of blade - near the blade tip, as shown in figure 3. The noise source can be divided into two main sorts according to inflow condition: airfoil self-noise and inflow-turbulence noise. Airfoil self-noise is caused by the interaction between boundary layer of blade and trailing edge of blade when turbulence is absent from inflow. Airfoil self-noise can also be separated into several categories according to different mechanisms, such as turbulent-boundary-layer-trailing-edge (TBL-TE) noise, laminar-boundary-layer-vortex-shedding (LBL-VS) noise, Trailing-edge-bluntness-vortex-shedding (TEB-VS) noise, separated flow noise and blade tip noise. The characteristic of airfoil self-noise may be tonal or broadband in accordance with their different categories. Inflow-turbulence noise is the noise generated by the natural inflow atmospheric turbulence encountering the blade. It can be classified into low-frequency inflow-turbulence noise and high-frequency inflow-turbulence noise depending on the relative size of turbulence eddy and blade chord. The sound power of both airfoil self-noise and inflow-turbulence

Figure 2. Components and total sound power level of a wind turbine [5].

Figure 3. Aero-acoustic noise sources of wind turbine blade [5].
noise are considered to depend on the inflow speed, angle of attack, airfoil shape and observation position.

The mechanisms and categories of wind turbine noise are reviewed in some details by Wagner [5]. TBL-TE noise is commonly considered to be the dominant noise source for modern large wind turbines [7, 8, 10]. Sometimes, inflow-turbulence noise may be prominent for some specific wind turbines [11, 12]. The relative importance of these two noise sources is dependent on the specifications of wind turbines [13]. TBL-TE noise and inflow-turbulence noise both are broadband noise. TEB-VS noise may be prominent when some special airfoil named blunt trailing edge airfoil is applied on wind turbine blade [14-16]. TEB-VS noise is a low frequency and tonal noise like mechanical noise, so when it appears we should think much of it.

3. Aero-acoustic noise prediction

The prediction methods of wind turbine noise include semi-empirical methods and complete numerical simulations. Semi-empirical equations were developed according to different noise mechanisms and validated by experiments [17-26]. The input to these equations includes the geometry of blade, operating conditions as well as details of boundary layer. It is necessary to couple the noise model to an aerodynamic model. The level of accuracy obtained by these semi-empirical equations is enough for the early phases of blade design when a fast and robust code is needed to assure the stability of the design procedure. So many researches are carried out around the validation and improvement of these semi-empirical methods in recent years [18-26].

Among the semi-empirical equations for airfoil self-noise, BPM equations are the most commonly used for its simplicity in form and input parameters. BPM equations are derived by Brooks, Pope, and Marcolini by acoustic and aerodynamic measurements of a NACA0012 airfoil in wind tunnel [17]. The empirical scaling laws for airfoil self-noise were fitted to the 1/3-octave spectra to derive these equations. Simple input parameters, such as boundary-layer thickness or displacement thickness, Reynolds number, inflow Mach number, and observation position, are needed for BPM equations. The boundary-layer parameters can be obtained by measurements or aerodynamic codes. Many works about the modification and validation for BPM equations are carried out because the equations are originally devised for NACA 0012 airfoil [18-20, 24-26].

TNO trailing edge noise model is a more sophisticated model for TBL-TE noise with more physical details than BPM equations. This new TBL-TE noise model was originally developed by Rene Parchen of TNO-TPD in the Netherlands [27]. It is based on the work of Blake [28] and uses the wave-number spectrum of unsteady surface pressures to estimate the far field acoustic pressure level. The wave number spectrum is assumed to be a function of some boundary-layer parameters: such as the mean flow velocity gradient, the RMS of normal turbulent velocity fluctuations, the integral length scale of the turbulence and a spectrum of normal turbulent velocity fluctuations on both sides of the airfoil. Far field noise can be obtained by this wave number spectrum on the assumption that the finite thickness of the trailing edge is negligible and the diffraction is similar to that of an idealized semi-infinite flat plate. The boundary-layer parameters in the wave number spectrum can be obtained by experiments or numerical simulation and their precision affect the far field noise prediction. NREL in USA and DTU in Denmark have carried out many researches to improve and validate TNO model by comparing with experimental results [21-23].

The original semi-empirical model for predicting inflow-turbulence noise was developed by Amiet [29-30] based on the assumption of a flat plate. It is modified by Guidati that allows modelling of different airfoils shapes [31-32]. The model of Guidati is based on an acoustic analogy and boundary-element method. In this model, the inflow turbulence is represented by harmonic gusts of vorticity that are assumed to passively convect along the streamlines of the steady mean flow around the airfoil. The model has been shown to predict the difference between different airfoil shapes correctly [20]. When this model is applied in the blade design procedure, the shortage of slowness of boundary-element method appears. Moriarty et al. developed a simplified model based on geometric parameters of six
standard wind turbine airfoils and a NACA 0012 and validated by experiments [21]. Despite of the advantages and disadvantages of these three models, they are still commonly used nowadays.

The complete numerical simulation methods for blade noise prediction are very active investigations in recent years. LES or LES/APE for near unsteady flow filed coupled with far field noise prediction by FW-H equation for penetrable surface have been developed for 2-D airfoil and 3-D blade [33-35]. In order to capture the acoustic signals in numerical simulation, cautions should be exercised for choosing numerical schemes and boundary conditions to assure low dispersion, low dissipation and non-reflections [36]. Time consumption is still very large for numerical simulations of blade noise although computer technology is developing fast nowadays. It is not suitable to adopt numerical simulation methods in the blade design procedure and semi-empirical methods are still popular. Numerical simulation methods are always used for deep investigation of noise mechanisms or validation for experiments and noise check when a blade has been designed.

4. Detection of noise sources by microphones array technique

It is important to find out what the noise generation mechanism is and where the dominant noise sources locate before we investigate how to reduce the noise radiation from wind turbine. In this section, microphone array technique is introduced and the latest results around the noise sources location work for wind turbines are reviewed.

Microphone array technique is the state of art technique to locate noise sources position. It has many applications such as for high-speed train [37], flying aircraft [38 - 39] and wind turbine [7, 8, 10, 12, 40, 41], etc.. A microphone array is composed of a number of microphones, the phase and amplitude of acoustic signal received by each microphone may be different due to their different distance from noise sources. Then the difference of phase and amplitude can be employed by some post processing algorithm to locate the positions of noise sources. The shape and size of microphone array, the distribution and number of microphones and the post processing algorithms may affect the source detection accuracy and some researches focus on these aspects [44 - 47], which is the basis of application for microphone array technique. Stefan Oerlemans gave a more detailed description about the basis of microphone array technique and some applications on the noise detection of wind turbines and aircrafts [48]. IET also has carried out some experiments and investigations on wind turbine noise by this technique [8].

Figure 4. Noise sources in the rotor plane (upper); Picture of microphone array (lower) [8].

Figure 5. Radial position of blade noise source varying with frequency for different rotor speed [8].
It is confirmed through experiments by microphone array technique that blade noise of modern large wind turbine is produced at the outer part of the blades (but not at the very tip), as shown in figure 4 [8]. It is observed that all prominent blade noise is produced during the downward movement of the blades. This strongly asymmetric source pattern can be explained by noise directivity. TBL-TE noise is analyzed to be the dominant noise source by normalized noise spectra comparisons based on the principle of wind speed dependence for noise level [7, 8].

There is another interesting thing observed that the radial position of noise source alters with frequency. The source moves outward with increasing frequency until it reaches the blade tip (44.1m), as shown in figure 5 and the source position is closer to blade tip for higher rotor speed when the noise source is at the same frequency. The radial movement of noise source position is an indirect indication that trailing edge noise may be the dominant source mechanism, for this phenomenon can be explained by the thinner trailing edge boundary layer due to high relative inflow velocity and smaller chord at higher radius [8].

Microphone array technique is still in the development of progress. It is believed that more and more interesting noise phenomena will be discovered with its developments.

5. Noise reduction

The noise radiated by a wind turbine depends on many variables like rotor speed, pitch angle, wind velocity, turbulence intensity, geometry of the blade, etc. The researches around noise reduction are always on the premise of minimum effect on power production. To achieve this goal two main measures are taken. The first one is through elaborate design for control laws to achieve minimum noise radiation from a manufactured wind turbine. The second one is considering noise reduction in the blade design procedure, which is the most promising and active in recent years.

Rotor speed and pitch angle are the two regulative variables when control laws are applied to reduce noise. It is clear that a decrease of rotor speed gives a diminution on noise radiation and a reduction on power output. It is inappropriate to reduce noise only by controlling rotor speed. The influence of pitch angle is a representation of angle of attack. An increase of pitch angle decreases the angle of attack of the blade inducing a thinner boundary layer on the suction side, then a diminution of noise. The effect is opposite on the pressure side. Since the detachment of the boundary-layer is firstly produced on the suction side, this side is commonly considered to be the strongest source of noise. Gemesa performed a series of systematic measurements by design a specific control version to allow modifying the pitch angle to obtain minimum noise for constant tip speed. Then semi-empirical correlations is obtained that could be applied in the design of low noise control laws. Ignacio has given a detailed description about this procedure [9]. Ignacio has also shown that when the effects of rotor speed and pitch angle both applied in the control laws to reduce noise, the power coefficients are closer to the maximum ones, as shown in figure 6. He points out that about a 1.5% of the production could be saved if the right control strategy is applied [9].

The most promising methods to reduce noise radiation from a wind turbine are to include noise effect during the blade design phase. Design of noise-optimized airfoils is one of these methods. Franck in Risoe [22, 25], Gemesa [9] and Lutz in University of Stuttgart [49] have designed and assessed noise-optimized airfoil through aerodynamic and acoustic wind-tunnel tests on 2-D airfoils. Lutz points out that the principle of the airfoil design was to reduce the dominant low-frequency (less than 1kHz) TBL-TE noise peak in the spectrum (which is due to the thick suction-side boundary-layer) by reducing the loading of the suction side, at the expense of an increased pressure-side loading (which causes a slightly higher noise level at less important medium frequencies of 1-3kHz) [50]. The wind-tunnel test showed 2-3dB reduction in average overall sound pressure level (OASPL) and an improved aerodynamic performance for the newly designed airfoils [51].

The concept of attaching sawtooth serrations or brushes on the blade trailing edge has been proved to be another effective noise reduction method. This concept was investigated in a number of experimental studies on 2-D airfoils [52, 53], model wind turbines [54, 55], and a full-scale wind turbine [56]. The latest noise experiments were carried out by the European 5th Framework project.
SIROCCO [51] on a GE 2.3MW test wind turbine with three different blades. One blade has serrated trailing edge at the outer 25% of blade where dominant noise emitted, the other blade is with noise-optimized airfoil and another blade is the normal blade [56]. Microphone array technique is applied to locate noise sources and reduction on each blade. The results show that average overall noise reductions of 0.5dB and 3.2dB were obtained for the optimized blade and the serrated blade, respectively. For both blades, the noise reduction increased with increasing wind speed. Although many experiments show good effect of serrated trailing edge on noise reduction, its mechanisms of noise reduction is not very clear at present and some experiments shown contradictions with the theoretical analysis [59]. The theory derived by Howe predicts that the higher \( h/\lambda \) is, the greater is the noise reduction, as shown in figure 8 [60, 61]. The results of experiments shown in figure 9 indicate different tendency [59]. The mechanisms of noise reduction by sawtooth serration need further investigation henceforth.

Another possibility method to reduce noise is to use of porous materials in the regions of blade where most noise is emitted, which is based on the principle that noise emitted by a surface depends...
on the acoustic impedance of the body. This concept is still at the stage of wind-tunnel research and has not applied on real wind turbine blades [62, 63].

6. Conclusion
Noise mechanisms and categories of modern large wind turbine are described. TBL-TE noise is commonly considered to be dominant. Inflow-turbulence noise may be prominent for some specific wind turbines. TEB-VS noise may be prominent when blunt trailing edge airfoil is applied on wind turbine blades. Some semi-empirical equations like BPM, TNO trailing edge noise model and Guidati model are introduced. These are commonly used in blade design procedure. Microphone array technique is applied for detection of wind turbine noise and some interesting phenomena of noise sources in rotor plane discovered by this technique are represented. Progress in noise reduction methods like elaborate design for control laws, noise-optimized airfoil and serrated serration on trailing edge are described and effects are shown. Although the turbine is restricted to horizontal axis wind turbines, the noise prediction model and reduction methods also can be applied to other turbines when the noise mechanisms are similar. Microphone array technique can be applied to locate any kind of noise sources.

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