



Experimental characterization of turbulent inflow noise on a full-scale wind turbine



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ABSTRACT

An extensive experimental campaign was conducted on a 108-m diameter 2.3-MW wind turbine in order to assess the effect of inflow turbulence conditions on wind turbine acoustics. Over 50 h of continuous acoustic data was acquired at power-generating wind speeds. Twelve precision microphones were used, arranged in a one rotor radius ring about the turbine tower in order to assess the directivity of the noise emission. Turbine operational and atmospheric conditions were gathered simultaneously with acoustics measurements. The testing and analysis constitute perhaps the most thorough experimental characterization of turbulent inflow noise from a wind turbine to date. Turbulence intensities typically varied between 10 percent and 35 percent, and wind speeds covered most of the operational range of the wind turbine, from cut-on to well above its rated power. A method was developed for using blade-mounted accelerometers for determining the turbulence conditions in the immediate vicinity of the blades, which are the primary turbulence noise generating bodies. The method uses the blades' vibrational energy within a specified frequency range to estimate the overall turbulence conditions by assuming a von Kármán turbulence spectrum. Using this method, a clear positive correlation is shown between turbulence intensity and noise levels. The turbulence noise is dominant at low frequencies and is primarily observed in the upwind and downwind directions. Low frequency noise increases by as much as 6 dB for the range of turbulence conditions measured. Comparisons are made between the measured turbine noise directivity and theory using a simple acoustic model of the turbine as three point-sources. Strong agreement is found between the theoretical leading edge noise directivity model and the measured low frequency noise directivity.

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1. Introduction

Significant research has been conducted into wind turbine acoustics in the past few decades because of the detrimental effect that the noise has on widespread development of the wind energy resource. Noise restrictions limit the areas in which wind turbines can be constructed. Furthermore, the noise is often cited as an irritant and can negatively affect the public

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perception and acceptance of wind power. A thorough understanding of the mechanisms by which turbines generate noise is necessary for logical placement of the turbines as well as for the development of noise mitigation methods.

The noise generated by modern industrial scale wind turbines is dominated by aerodynamic noise sources on the turbine blades [1,2], each ultimately caused by some form of unsteady flow about the blade. Turbulent inflow noise (TI noise) is caused by atmospheric turbulence in the inflow field of a turbine interacting with the blades. The unsteady pressures resultant on the surface of the blades then radiate as sound according to the unsteady surface pressure theory of Curle [3]. A similar phenomenon is caused by turbulence in the aerodynamic boundary layer of the blades interacting with the discontinuity of trailing edge, which is known as turbulent boundary layer trailing edge noise (TE noise). That is, at the Reynolds numbers relevant to modern large wind turbines the aerodynamic boundary layer about a blade transitions naturally to a turbulent state, and this self-generated turbulence causes surface pressure fluctuations near the trailing edge and noise. Oerlemans et al. [2,4] showed that TE noise dominates the mid- to high- frequency range—specifically, A-weighted overall noise levels—for a 2.3-MW turbine and a 850-kW turbine, and that the noise can be well predicted using a modified version of the semi-empirical TE noise model developed by Brooks et al. [5]. It was also shown that the noise source can be mitigated significantly by design of the trailing edge features [6].

The behavior of TI noise from wind turbines is less well established. While numerous prediction models that include TI noise have been implemented, experimental validation has been limited. Grosveld [7] developed one of the first prediction models not based simply on empirical results. The model predicts TI noise based on a distributed dipole source approximation, and TE noise based on the model of Schlinker and Amiet [8], which was originally applied to helicopter rotor noise. Grosveld's model was validated using single-microphone measurements at various downwind and upwind positions. Notably, turbulence conditions were not measured during testing but were instead based on an assumed spectral shape scaled by a simple function of wind speed and height above the ground. The TI noise predictions were then tuned to acoustic measurements. The model predicts TI noise to be stronger than TE noise for the entire measured spectrum for an upwind-rotor, two-bladed, 1-MW machine, but Lowson [9] later points out that this result was produced in error; correction of the error would lead to a more balanced noise contribution from the two mechanisms, with TI noise dominating the low frequencies and TE noise dominating at high frequencies. Lowson also developed a prediction model, which differs from Grosveld's, for one, in that it uses a frequency dependent function for TI noise based on the flat plate airfoil analytical predictions of Amiet [10]. Again, validation was carried out without direct measurement of turbulence conditions, and TI noise predictions were tuned to single-microphone measurements.

Moriarty et al. [11,12] developed the acoustic prediction code for the National Renewable Energy Laboratory's (NREL) wind turbine computer-aided engineering tool FAST. The model includes a TI noise model based on Amiet's model combined with the modifications for finite thickness airfoils and angle of attack developed by Guidati et al. [13]. Turbulence conditions were measured during model validation using ultrasonic anemometers located on a meteorological tower upwind of the turbine. Agreement between predictions and observations are variable within this body of work. In particular, Moriarty notes a case where the non-stationarity of flow conditions—i.e. strong wind gusts—cause an unreasonably large prediction of TI noise. The wind speeds from this 1-min measurement varied rapidly between 2 m/s and around 10 m/s resulting in a calculated turbulence intensity value of 46 percent, which is then fed to the noise prediction code. The issue here is that the gusts contributing to this turbulence intensity value comprise frequencies much lower than those of interest to acoustics—periods are on the order of a minute. This issue of non-stationarity is addressed in the analysis that follows. In general, it does not appear that enough data was gathered to confidently determine the accuracy of the TI prediction model or to correlate measured low frequency noise to inflow turbulence conditions.

The work presented herein is intended to build upon these previous bodies of research by definitively characterizing the effect of turbulence in the inflow field of a wind turbine on its acoustic emission. A large volume of experimental data is analyzed, for which both the atmospheric conditions and acoustic emission of the turbine are thoroughly captured. A novel method of characterizing the turbulence is also developed based on accelerometer measurements of turbulence-induced blade vibrations. The method allows for assessment of turbulence conditions directly in the rotor plane and also alleviates the issues of non-stationarity observed by Moriarty [14] by measurement of only relatively small scale turbulence. A consistent relationship is observed between turbulence conditions and noise, particularly at low frequencies, constituting perhaps the most thorough experimental analysis of the effect of turbulence levels on wind turbine noise to date. Finally, several possible mechanisms for the observed behavior are discussed in order to further clarify its nature and cause, showing by far the most consistency with the expected behavior of TI noise.

2. Experimental methods

This section describes the tools and methods used for the analysis of the effects of turbulence on wind turbine acoustics. The facilities and data acquisition systems are first detailed. A description is then given of a turbulence measurement technique developed specifically for this study, which uses the measured vibrations of the blades as a proxy to the turbulence conditions in the rotor plane.

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