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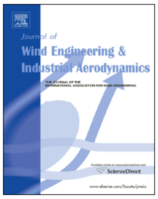

A discussion of wind turbine interaction and stall contributions to wind farm noise

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ABSTRACT

Wind farms have recently been reported to produce a noise signature that is described as possessing a “thumping” quality. Measurements of these signatures are limited and their effects are debated but their effect on public opinion and complaints make them a concern for researchers in this field. Proposed reasons for these noise signatures include amplitude modulation, interference patterns and wake–rotor interaction. This paper discusses these effects and concludes that wake–rotor interaction plays a role by causing variations in turbulent-inflow noise and dynamic stall. The current state of research into stall noise and wind turbine wake structure is also reviewed and it is concluded that the available information and collected data on wind turbine wake are insufficient to determine how strong this role is. More information on the velocity and turbulence fields in the wake of horizontal-axis wind turbines as well as a characterisation of the noise produced by an airfoil experiencing dynamic stall is required in order to make a full assessment of rotor–wake contributions to wind farm noise.

1. Introduction

In the past few years there has been substantial growth in the non-hydroelectric areas of the renewable energy sector, with production capacity globally increasing by 21.5% between 2011 and 2012 (Sawin, 2013). Some elements of these technologies result in reduced economic viability or public acceptance which limits growth. Advancements that address these concerns, such as improvements to efficiency and better noise control, are necessary in order for rapid growth to continue.

Wind power was the fastest growing renewable in 2012, accounting for 39% of global added capacity (Sawin, 2013). Given that wind speed increases with distance from the ground, larger wind turbines are constantly being developed in order to take advantage of this. A greater swept area enables more wind energy to be captured and the increase in height gives them more reliable access to high wind-speeds. Being able to access higher wind speeds more reliably increases the capacity factor of large turbines resulting in a lower levelised cost of energy compared to smaller models (Bolinger and Wiser, 2012). However this increase in size can have adverse effects on the turbine's noise spectrum and its efficiency in an array configuration.

Wind turbine noise control is becoming increasingly problematic as wind turbines grow larger, as they individually emit more noise and the low frequency component of their spectrum grows (Møller and Pedersen, 2011). Low frequency sound is attenuated less by the atmosphere than high frequency sound which makes large wind turbines audible from further away (ISO, 1993). There is a significant amount of negative public opinion with regards to wind turbine sound emissions due to the reported “annoying qualities” they possess. These are qualities of the sound that would increase the annoyance of wind turbine noise above that of equivalent A-weighted broadband noise level (Persson Waye and Öhrström, 2002). Low-frequency sound with these qualities will therefore have a greater effect on a wider area than high-frequency noise sources. Many regulations require that an extra 5 dB is added to the noise level to compensate for increased annoyance if these qualities are present (EPA South Australia, 2009; NSW Department of Planning & Infrastructure (NSW DPI), 2011). These legal restrictions on sound pressure level/exclusion zones near residential areas encourage shorter distances between turbines in a wind farm. However close spacing creates the possibility that the wind turbines in a farm will adversely interact with each other, which can lead to unsteady blade loading, reducing power output and increasing noise level and blade fatigue (Högström et al., 1988; Thomsen and Sørensen, 1999). An understanding of the mechanisms of wind farm noise production is required in order to continue to comply with noise limits and understand adverse interactions between turbines in a wind farm.

Unsteady blade loads stem from variations in velocity and turbulence. Incoming wind will always possess these qualities, so wind turbines will always experience unsteady loading to some extent. Understanding how higher levels of unsteady inflow resulting from operating in the wake of another turbine affect this loading is important.

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The authors posit that inflow turbulence due to wake-interaction is a significant source of noise with these reported qualities. This can manifest as periodic increases in noise level due to changes in angle-of-attack and separation effects, dynamic stall and blade–vortex interaction. Several questions need to be answered before a conclusion can be reached on this matter.

- Are large-scale turbulent structures present in the far wake of a wind turbine?
- How are the wake and its parameters affected by wind gusts?
- Will the blades of downstream turbine(s) be adversely affected by these structures?
- Will this interaction generate noise and what qualities will that noise have?

Once the answers to these questions are known whether wake–rotor interaction is contributing significantly to wind turbine noise can be determined.

Determining the loading due to unsteady flow requires definition of the flow-field, but wake structure is complicated. Due to this complexity most studies only analytically model parameters in a one-dimensional or axisymmetric fashion (Vermeer et al., 2003). These simplified models are suitable for typical power prediction and layout optimisation but are too simple to properly predict unsteady loading and noise. Understanding of how the wake affects downstream turbine is greatly hindered unless computational or experimental data is used. Computational simulations often implement actuator line, actuator disc or blade element momentum models, which approximate the blades as lines or discs that apply a force to the fluid. This approach is much faster than full modelling of the blades, and suitable for most applications but occasionally insufficient. Recently large-eddy simulations (LES) of the wakes of horizontal-axis wind turbines have been conducted (Bazilevs et al., 2011, Jimenez et al., 2007, Hsu et al., 2014, Porté-Agel et al., 2011, Sezer-Uzol and Long, 2006). This is a turbulence model that directly resolves large-scale eddies and models smaller ones, eliminating the extra computational cost of simulating very small scale turbulence. There is often cross-over in these approaches, with LES studies using actuator line or disc methods (Jimenez et al., 2007; Porté-Agel et al., 2011). Using simplified approaches instead of modelling the blades directly may lead to missed details in the wake flow-field and airfoil noise. Differences in the approaches are largest in the near-wake, but may result in other changes in wake structure further downstream (Réthoré et al., 2011). Investigations of far-wake turbulence line actuator methods are currently appropriate because such downstream differences are not known to occur in wind turbine wake simulations (Shen et al., 2012). If any discrepancies are found between the full rotor and actuator line or actuator disc models the new information can be added to these models in the form of corrections.

LES enables high fidelity simulations on a range of scales without prohibitive computational cost. Resolving structure in the velocity field in the downstream region where other turbines operate requires high fidelity models such as LES. If there is a large amount of large scale structure in the wake in this region then angle-of-attack and blade–vortex interaction effects will become significant. Changes in airfoil spectra due to these effects are understood well enough to suggest that they will increase the low frequency component of wind turbine noise. However characterisation of the noise due to dynamic stall is still required, which presents a significant challenge to determining the contribution of wake–rotor interaction.

2. Adverse wind farm noise characteristics

Most wind farm noise is broadband—that is its spectrum contains a wide range of frequencies with no large spectral peaks. While some tonal noise is produced in the mechanical components of the turbine it is drowned out by the stronger aerodynamic noise sources.

Studies into how this noise affects humans show that under certain conditions the annoyance rating by test subjects will increase. In addition the closer the subject is to the source the greater this effect becomes and a greater decrease in the ability to perform cognitive tasks occurs. Qualities of the noise such as frequency content have also been found to have an effect, with low-frequency noise being reported as more annoying (Nobbs et al., 2012).

Other factors also need to be considered as visual stimuli have been found to mitigate these effects, and parameters such as turbine colour have also been weakly linked to the reported annoyance (Iachini et al., 2012; Maffei et al., 2013; Ruotolo et al., 2012). This is of concern as many studies report that exposure to high enough levels of noise can disturb sleep leading to increases in stress (Pedersen et al., 2009). When trying to sleep there is a lack of visual stimuli which may result in disturbance from noise that is not disturbing at other times of day.

Despite these factors many residents near wind turbines report no ill-effects. In addition to this some aspects of wind turbine noise complaints suggest psychosomatic elements (Farboud et al., 2013). It is not currently known whether this is the case, but as the noise signatures can vary with location it is possible that only some households are affected.

Other studies of the characteristics of wind turbine noise report complaints of subjective or descriptive measures. These studies report complaints due to qualities referred to as “swishing”, “thumping” or “throbbing” (among others), which often occur at the blade pass frequency (Oerlemans and Schepers, 2009; Pedersen et al., 2009; Pedersen and Persson Waye, 2004; Persson Waye and Öhrström, 2002; Van den Berg, 2004). Characterisation of these noise qualities is hindered by the subjective and interchangeable use of the terms “throbbing”, “swishing” and “thumping” in the literature. This is due to the terms being used by residents near wind turbines to describe their experiences. Amplitude modulation, which is a periodic variation in sound level is defined by a modulation frequency (the distance between peaks) and a modulation depth (the size of the amplitude change), is considered the cause of these effects. These qualities are hard to categorise as few studies report on both the descriptors used by residents and the properties found in the noise recordings. It is likely that some, if not all, of the aforementioned characteristics stem from amplitude modulation of different noise sources but to the authors' knowledge there is no standard quantitative definition of each descriptor.

These descriptors are useful for targeting further research into some of the poorly understood intermittent phenomena that may go unnoticed in large-scale experiments. Measurements have found that short periods of amplitude modulated noise sometimes occur at night in the signature of the Rhedes Park wind farm, as shown in Fig. 1, but this variation has not been observed to this degree in a single turbine (Van den Berg, 2004). Mechanisms for the production of this noise have been suggested; including velocity gradients, turbulent inflow, interference patterns and blade–tower interaction but the cause is still disputed and will be discussed further in the next section.

It is possible that the use of different descriptors in qualitative studies is due to the changes in the characteristics of amplitude modulated noise over time. Fig. 2 shows a turbine spectrogram that transitions from modulated low-frequency to modulated high-frequency noise (Smith et al., 2012).

To summarise, there are a large number of descriptors that have been used when people living near wind farms report their experiences listening to turbine noise. As they have stemmed from subjective surveys they are not yet well quantified which both hinders and assists attempts to classify the noise that people in