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Wind farm noises: Mechanisms and evidence for their dependency on wind direction

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ABSTRACT

The mechanisms responsible for swishing and thumping noises generated by wind turbines are unclear and the existence of which have significantly affected the perception of wind energy by the community. To better understand the nature of this noise source, this study, for the first time, investigates the correlation between the potential noise generation mechanisms in wind farms and the characteristics of the perceived noise reported by residents in the vicinity of the farms in survey data. Published reports and measurements show that in addition to the perceived noise near the turbines, the thumping noise, in general, is perceived far downstream of the turbines. Normal swish perceived in a short distance from a wind turbine, especially in the cross-wind directions, can be explained by the convective amplification and directivity of the trailing edge noise. As will be discussed in this article, there exists strong evidence that the dominant mechanism of wind farm noise is associated with amplitude modulation of the aerodynamic noise by the eddies generated when the turbine blade partially stalls or due to an interaction with the turbine wake. This hypothesis is primarily based on the low frequency characteristics of the stall and also the distance and direction of the noise propagation. Moreover, it is hypothesised that the wake supplements this effect as it results in refraction and modulation of the emitted noise.

1. Introduction

Wind energy has had the fastest growth rate among the renewable sources of energy over the past few decades due to its competitive price and mature technology. This has resulted in the widespread deployment of wind turbines in rural communities, which, despite resulting in some economic and environmental benefits, has led to negative community impact, such as health concerns, which in turn, are hypothesised to be related to the wind turbine noise [1–5].

Wind turbine noise can be categorised into two groups [6–9]: a) mechanical noise, which is well studied and understood, can be easily mitigated and can usually be perceived only in the vicinity of a turbine [10]; b) aeroacoustic or aerodynamic noise which is generated due to fluctuating forces interacting with the blades of the wind turbines. There exist several mechanisms contributing to the generation of aerodynamic noise from a wind turbine such as: turbulent inflow, turbine blade stall, blade trailing edge, blade-tower interaction, blade tip and laminar boundary layer vortex shedding [11]. The last two mechanisms are predominantly high frequency signatures and are unlikely to play significant roles in perceived noise far from the wind turbines. While blade-tower interaction has been reported as a major noise source for downwind turbines due to interaction of the blade and vortex shedding from the tower, studies show that the effect of perturbed flow upstream of the towers of modern upwind turbines is not significant in generation of unsteady loads on the blade compared to the load variation due to interaction of the blade with the incoming turbulence [12]. Moreover, the level of noise generated by the blade-tower interaction also decreases as the mean wind speed and yaw error increase, while the level of noise generated by other mechanisms increases under these conditions [12,13]. In addition, the noise generated due to the blade-tower interaction occurs at the blade pass frequency and may contribute to the infrasound (frequency less than 16 Hz) [14,15], hence it is not the objective of this study which investigates only the audible sound.

To explain the mechanisms which are believed to be the main sources of the noise generated by wind turbine blades, a schematic of the flow over a blade is shown in Fig. 1. When the blade encounters turbulence eddies from incoming flow, fluctuating forces on the blade surface result in noise generation. The frequency of the emitted noise has an inverse relationship with the size of the

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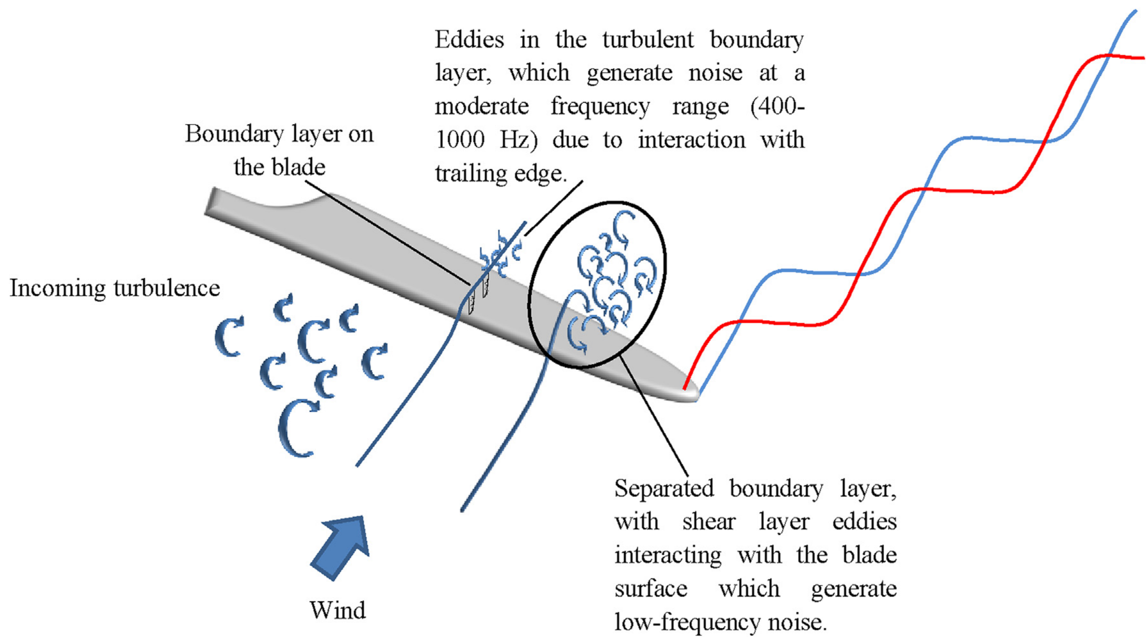

Fig. 1. Incoming flow features and different noise generation mechanisms.

incoming eddies such that the larger eddies generate noise at lower frequencies compared with the noise generated due to interaction of the blade with smaller eddies [16,17]. Trailing edge noise is generated by the eddies in the scale of boundary layer displacement thickness at the trailing edge of the airfoil, which results in fluctuating forces at a moderate frequency (400–1000 Hz) [7,11]. Stall and consequent vortices generated due to the flow separation also result in fluctuating load on the airfoil and if the deep stall occurs large eddies will form on the suction of the airfoil which result in a significant increase in noise level at an audible lower range of frequency (100–400 Hz) [11,18].

Amplitude modulation is also another mechanism, which affects the emitted noise from wind farms and has been reported to be one of the reasons of perceived annoying noise [11,19]. Amplitude modulation is characterised by a variation of the level and character of noise in time. The normal amplitude modulation is caused due to variation in noise level due to movement of the source of the trailing edge noise during the rotation of the blade. Normal amplitude modulation of broadband trailing edge noise occurs at blade pass frequency with the fluctuation of a few decibels and is perceived in close distance of wind turbines [11]. There exists another type of amplitude modulation, so called Other Amplitude Modulation (OAM) or Enhanced Amplitude Modulation (EAM), which has stronger low-frequency content and increased depth of the modulation (6–12 dB) [11,20]. EAM can be caused by the partial or transient stall on the blade when the blade interacts with incoming eddies, turbine wake or inclined flow. Since most of the survey data are collected far downstream of the turbines it can be concluded that EAM or OAM can be the underlying mechanism for perceived noise. As will be discussed further in the text and in section 3.

Two main features of the aerodynamic noise are noticeable: a) "***swish***" which has broadband content and directed towards the leading edge, generated primarily due to turbulent boundary layer interaction with the trailing edge of the turbine airfoil; b) "***thumping***" at the blade pass frequency which travels a few kilometres and is known to have the most annoying effect on people [9,21–24]. This article investigates the above sources of noise with a focus on thumping as explained above.

In the past decades a large number of scientific articles have been published on the mechanisms of noise generation from wind turbines with the main focus on reporting the outcomes of laboratory experiments and numerical modelling [11,25–29]. In contrast to the published literature, this article for the first time is based on the statistical analysis of the recorded complaints by the residences in the vicinity of wind farms. This has been done in an attempt to draw a correlation between the sound directivity, the prevailing wind direction and the blade angle of attack. In this paper, a meta-data analysis has been conducted based on the reported noise perception surveys combined with the publically available information on the directivity of the airfoil noise at different pitch angles. This approach is used in order to provide a quantitative support for the hypothesised underlying physical mechanisms for noise generation. This can contribute significantly to the field, since the outcomes of this work can be used by wind farm designers and decision makers to identify the source of the noise observed at residences, which potentially can be used in the design of future wind farms. In the following section, the main mechanisms for airfoil noise are described and the survey data from the residents in the vicinity of four wind farms are analysed to establish a relationship between the perceived noise and the associated mechanisms. A data analysis approach is utilised in the next section to determine the dominant underlying mechanism for wind turbine noise. This section is followed by a discussion and summary of the outcomes from the statistical analysis of the survey data to conclude the possible noise generation mechanism.

2. Directivity of the perceived noise

Fig. 2a shows a typical wind turbine. The turbine blade is generally twisted such that the airfoil reaches its maximum pre-stall angle of attack along its span when it rotates at its nominal rotational speed [30,31]. The directivity of the trailing edge and stall noise is shown at three segments of the blade in Fig. 2b. As shown on Fig. 2b, the trailing edge noise is largest along the airfoil chordline and towards the leading edge, which means it tends to be perceived at the locations approximately perpendicular to the relative wind direction [17,32]. Due to higher attenuation rate of the