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Location of aerodynamic noise sources from a 200 kW vertical-axis wind turbine

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ABSTRACT

Noise levels emitted from a 200 kW H-rotor vertical-axis wind turbine have been measured using a microphone array at four different positions, each at a hub-height distance from the tower. The microphone array, comprising 48 microphones in a spiral pattern, allows for directional mapping of the noise sources in the range of 500 Hz to 4 kHz. The produced images indicate that most of the noise is generated in a narrow azimuth-angle range, compatible with the location where increased turbulence is known to be present in the flow, as a result of the previous passage of a blade and its support arms. It is also shown that a semi-empirical model for inflow-turbulence noise seems to produce noise levels of the correct order of magnitude, based on the amount of turbulence that could be expected from power extraction considerations.

1. Introduction

With the current rapid increase in the number and size of wind-power installations worldwide, it is important to consider different environmental aspects of this expansion. Wind power shows a potential of supplying a major fraction of the global energy demand [1], and such a penetration will lead to an increased number of people living near wind turbines. Thus, aspects such as low noise and appealing aesthetics are likely to be key factors for this expansion to acquire general acceptance. This motivates the evaluation of new wind-power concepts with respect to these aspects, especially noise performance.

Vertical-axis wind turbines (VAWTs) have been proposed as an alternative to the more common horizontal-axis wind turbines (HAWTs). Overshadowed by the commercial success of the HAWT design, which is now a big industry, the VAWT concept has several features that still make them interesting to study. The VAWTs typically have fewer moving parts and a generator located at ground level, which could ultimately lead to higher availability and lower maintenance costs [2]. Additionally, due to a lower tip-speed ratio (TSR), the VAWT concept has been anticipated to allow lower noise levels.

Noise from operating wind turbines can be divided into aerodynamic and mechanical noise. Aerodynamic noise is of broadband character and originates from various complex flow phenomena when the air flows around the turbine. Mechanical noise originates from the relative motions of various mechanical components. For modern turbines, the

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Nomenclature

A	Cross-section area of turbine, m^2
A_t	Cross-section area of turbulent volume, m^2
c	Airfoil chord length, m
c_0	Speed of sound, m/s
C_p	Power coefficient
$\overline{D}_L$	Directivity factor
f	frequency, Hz
I	Turbulence intensity
k	Local wave number
k_e	Wave number of the energy-containing wavelength scale
$\overline{K}$	$kc/2$
ℓ	Turbulence length scale, m
L	Blade span, m
M	Local Mach number, U/c_0
P	Power, W
r	Source-to-observer distance, m
r_e	Retarded source-to-observer distance, m
S	Compressible Sears function
S_0	Reference area of 1 m^2
u	Wind speed, m/s
U	Local velocity over the airfoil, m/s
v_{blade}	Blade velocity, m/s
α	Measurement-position angle
β	$1 - M^2$
Φ_e	Angle specifying the retarded observer position
ρ_0	Density of air, kg/m^3
θ	Blade azimuth angle
Θ_e	Angle specifying the retarded observer position
LFC	Low-frequency correction
SPL	Sound-pressure level, dB or dBA, reference value 2×10^{-5} Pa
SWL	Sound-power level, dBA, reference value 10^{-12} W
TKE	Turbulent kinetic energy, m^2/s^2
TSR	Tip-speed ratio

aerodynamic noise is generally dominant [3]. The VAWT design allows for the drive train to be located at ground level, which may further limit mechanical noise propagation [2].

Extensive research has been presented regarding noise from wind turbines (see, e.g., [4–7]). Most of this research focused on noise from HAWTs, motivated by the large number of installed HAWTs and reported annoyances at some installations. In [4], it was shown that, for a modern HAWT, most of the noise is created close to the blade tip when the blade travels downwards (toward the receiver). This aerodynamic noise was identified as turbulent-boundary-layer trailing-edge (TBL-TE) noise, and the result is an amplitude-modulated characteristic swishing, due to the directivity of the trailing-edge noise and convective amplification. This mid-frequency phenomenon (400–1000 Hz) has been found to be the most annoying [3]. Interaction between inflow turbulence and the airfoil leading edge also generates noise, which generally dominates the low-frequency part of the HAWT noise spectrum [8].

1.1. VAWT noise generation

The generated aerodynamic noise generally increases with the local speed of the blade. The VAWTs usually have lower TSR than HAWTs. Lower levels of aerodynamic noise might then be expected for a VAWT due to the relatively low blade velocity compared to HAWTs. However, there are important differences between these designs with respect to noise generation. First, VAWTs encounter highly unsteady flow properties and varying angles of attack (e.g., dynamic stall at low TSR [9]). Second, at the downstream half of the rotation, the blades of a VAWT pass the wake of the blades at the upstream half [10–12]. The turbulence levels at the downstream half of a VAWT are expected to be much larger than the turbulence of the flow ahead of the turbine.

Tonal components, mainly harmonics of the blade-passage frequency, are generally expected to be present in the VAWT noise spectrum due to the unsteady blade loading [13]. However, for large VAWTs, the blade-passage frequency and a major part of its harmonics fall outside the audible frequency range.

1.2. VAWT noise prediction

A few recent studies have specifically considered noise prediction in the context of VAWTs. In [13], the noise characteristics of a model VAWT were investigated and the applicability of different noise-prediction models was examined. Both the harmonic content and the broadband content were modeled. In [14,15], two-dimensional (2D) vortex methods were used to simulate aerodynamic noise from VAWTs. Both studies indicate lower noise levels compared to HAWTs. The VAWT noise studies based on 2D CFD setups were presented in [16,17], the latter including experimental validation using a small VAWT at very low TSR. In [18], noise predictions using a semi-three-dimensional large-eddy simulation were performed, and [19] used an unsteady three-dimensional (3D) inviscid panel method to predict parts of the noise spectrum.

These studies consider small turbines and/or simplified geometries, which limit their applicability for large VAWTs. Initial noise-emission measurements of the 200 kW VAWT considered in this study were presented in [20], where it was suggested that the noise from VAWTs of this size is likely to be of a different origin than the trailing-edge noise dominant for large HAWTs.