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Experimental Measurements of Rotating and Stationary Wind Turbine Rotor Blade Noise

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Abstract

A wind turbine rotor has been constructed for the investigation of airfoil self-noise, rotational noise and blade tower interaction noise. The main aim of this paper is to compare the aerodynamic noise created by stationary and rotating rotor blades. Furthermore, the effect of the tower on noise production, the so called blade tower interaction noise, has also been examined. A peak in the trailing edge noise spectrum has been observed in stationary and rotational blade noise spectra supporting previously published measurements. The effect of the tower was observed at low frequencies, due to the change in aerodynamic loading, and at high frequencies, due to acoustic scattering phenomena.

Introduction

Wind turbine noise is a subject of great importance as people living nearby wind farms report to be annoyed by the associated noise. It is very likely that wind turbine noise will become more of a problem due to predicted increases in future wind turbine size, which makes the need for improved understanding of the noise generating principles even more important. Previous studies which addressed the relationship between the aerodynamics of a wind turbine and far field noise, concentrate either on the acoustics or the aerodynamic aspects and thus the link between the noise and its production mechanism is not fully understood.

A wind turbine is a three-bladed subsonic, low-solidity device that operates within the atmospheric boundary layer. Wind turbine noise at low frequencies is dominated by discrete tones at the blade pass frequency (BPF). This periodic loading is caused by steady and unsteady aerodynamic forces acting on the blades. Steady aerodynamic forces have been linked to the tonal acoustic spectrum by Gutin [6]. Gutin's theory can only predict the lowest harmonics of the BPF, while the upper harmonics are attributed to unsteady periodic loading [12]. The effect of the steady aerodynamic force is usually neglected in wind turbine noise studies due to the low rotational speed.

The unsteady aerodynamic force, on the other hand, can be exerted on wind turbine blades via several different mechanisms such as that associated with the velocity deficit infront of the tower, for example [5]. The resulting noise is referred to as blade tower interaction (BTI) noise. By taking into account the average rotational speed of a wind turbine ($\sim$18 RPM), the BTI noise source operates in the infrasound region ($\sim$1 Hz). It is important to study this sound source because of low acoustic absorption at these low frequencies which means that the sound may be noted at long distances from the wind farm [13].

Trailing edge noise is the most important aerodynamic noise generating mechanism on a modern wind turbine [10]. This noise is created when turbulence in the boundary layer convects past the trailing edge, where it faces a sudden impedance change that scatters the hydrodynamic pressure, producing farfield sound [3].

Brooks, Pope and Marcolini [1] provide the most comprehensive trailing edge noise data set for a NACA 0012 airfoil at various angles of attack, chord lengths and Reynolds numbers. These authors formulated a semi-empirical model (the BPM model) for predicting 1/3 octave band sound pressure levels which is used for wind turbine noise prediction models [8, 9]. According to the BPM model, the sound pressure level is a function of the boundary layer thickness, blade Mach number and distance between the source and the observer.

Doolan and Moreau [4] provide an excellent review of trailing edge noise experimental data in which they found a consistent "low-frequency" peak at Strouhal number (based on δ^* and U_∞) of $\sim$0.069. The peak existence has also been shown in computational models [11], which means that the peak cannot be attributed to facility effects. However, a debate about the fundamental nature and importance of that peak is ongoing. It is an opinion of Doolan and Moreau [4] that the peak is important because it contains a significant amount of energy in the audible frequency range, at a Reynolds number applicable to current and future wind turbines [2].

Very little, if no, literature is available regarding direct comparison of stationary and rotational airfoil self-noise production mechanisms.

Methodology

The main aim of the experiments was to simultaneously study stationary airfoil self noise and rotational blade noise emissions. Experiments were performed in the anechoic wind tunnel and the anechoic chamber at the University of Adelaide. The blades were tested under stationary conditions in the anechoic wind tunnel and under rotational conditions in the anechoic chamber.

The anechoic chamber surrounding the wind tunnel is approximately 8 m^3 in size and provides reflection-free acoustic environment down to 200 Hz [7]. The contraction outlet is rectangular in cross section and has dimensions of 75 mm $\times$ 275 mm as shown in figure 1.

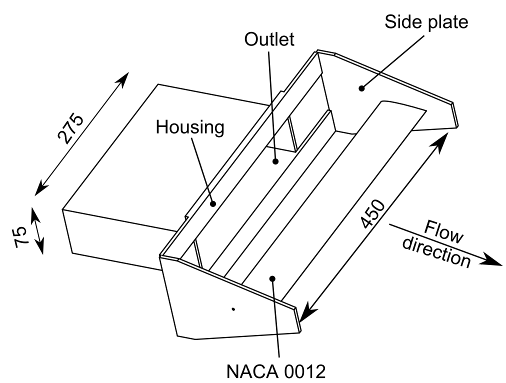

Figure 1: Schematic of blade mounting in the anechoic wind tunnel.

The blade had a chord of 70 mm, span of 450 mm and it was tripped with 0.5 mm thick “3D turbulator” tripping tape. The blade was secured to the housing, which was attached to the outlet contraction, at 0° angle of attack. The span of the blade extends beyond the width of the wind tunnel contraction outlet which eliminates the noise of plate boundary layer interaction with the leading edge of the blade. The blade mounting arrangement is illustrated in figure 1.

The measurement set-up is outlined in figure 2. The boundary layer thickness (δ) was measured with a single hot-wire probe positioned 0.5 mm downstream of the trailing edge at a flow speed of 30 m/s and turbulence intensity of 0.3%. Far field noise was measured with a single $1/2''$ free field B&K 4190 microphone positioned at $R = 0.55$ m and $\Theta = 85^\circ$. All data was recorded using a PXIe-4499 24bit National Instruments acquisition card.

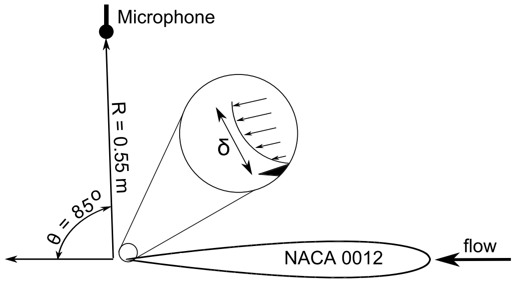

Figure 2: Measurement set-up in the anechoic wind tunnel.

A wind turbine rotor, shown in figure 4 was used to investigate noise from the rotating blades. The model constitutes 3 NACA 0012 tripped blades, spaced 120° apart. A slip ring, with 24 channels, is located behind the rotor plane. The slip ring allows transfer of the electrical signals from the rotor plane to a data acquisition unit. Behind the slip ring there is a torque sensor, which provides control over the blade angular position. All elements are shown in figure 4.

The wind turbine model noise emissions can be controlled via three adjustments; change in distance between the tower and the rotor plane (tower clearance), change in angle of attack and change in the rotational speed via an AC driver.

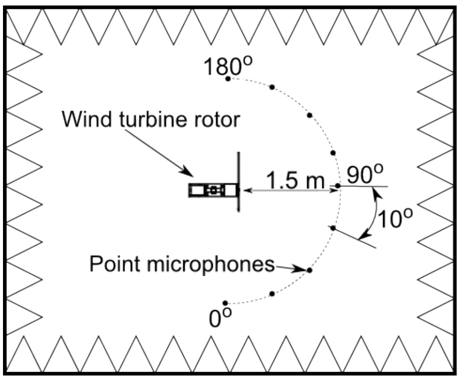

Figure 3: Measurement set-up in the anechoic chamber

The anechoic chamber has dimensions of 4.79 m × 3.9 m × 3.94 m which gives the volume of 73.6 m^3. The chamber is anechoic down to 100 Hz. The anechoic chamber measurement set-up is outlined in figure 3. Point microphones, $1/2''$ free field B&K 4190, were positioned 1.5 m from the rotor plane in a half circle, spaced 10° apart. The signals were recorded using a 9234 24bit National Instruments acquisition card.

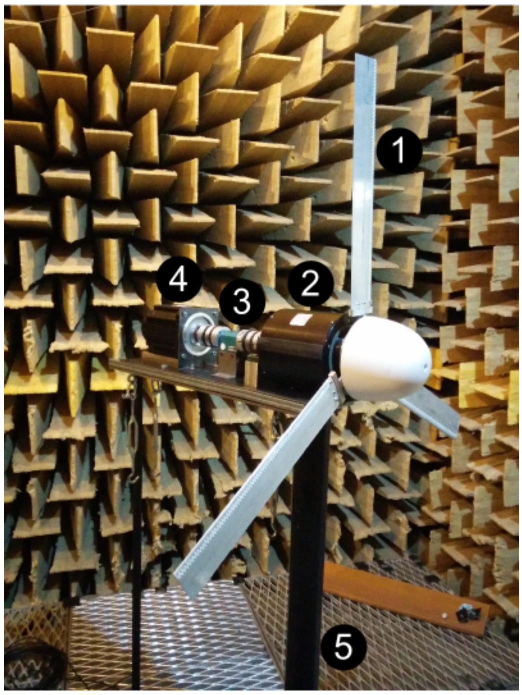

Figure 4: Wind turbine model. Parts are:*(1)* NACA 0012 airfoil (tripped at 10% chord length, 70 mm chord, 450 mm span), *(2)* Slip ring, *(3)* Torque sensor, *(4)* AC driver and *(5)* Tower (70 mm outer diameter).

The aeroacoustic investigation of the rotor model was conducted at 20 mm and 70 mm tower clearance distances and at 900 RPM (52 m/s blade tip speed). The blades were mounted at 0° angle of attack.

Preliminary results

The boundary layer thickness measured on the stationary airfoil in the anechoic wind tunnel was 5.6 mm and the boundary layer thickness on the rotating airfoil was estimated to be 3.9 mm at the blade tip, using the BPM model formulation [1]. The position at the blade tip was chosen because the majority of noise, > 5 kHz, originates at the blade tip or very close to it according to beamforming measurements which are not presented in this paper. Frequency scaling, based on the Strouhal number, between the stationary and rotational blade is not straight-forward due to the variable flow conditions experienced by the rotational blade. However, the Strouhal number, $St = \frac{f\delta^*}{U_\infty}$, for the rotating blade was determined according to the blade tip speed $U_\infty = 52$ m/s and the 0.48 mm boundary layer displacement δ^* at the trailing edge. The boundary layer displacement was obtained from the boundary layer thickness according to: $\delta = \delta^* \times 8$. A one-third octave sound pressure level comparison between the stationary airfoil and the wind turbine rotor can be seen in figure 5.

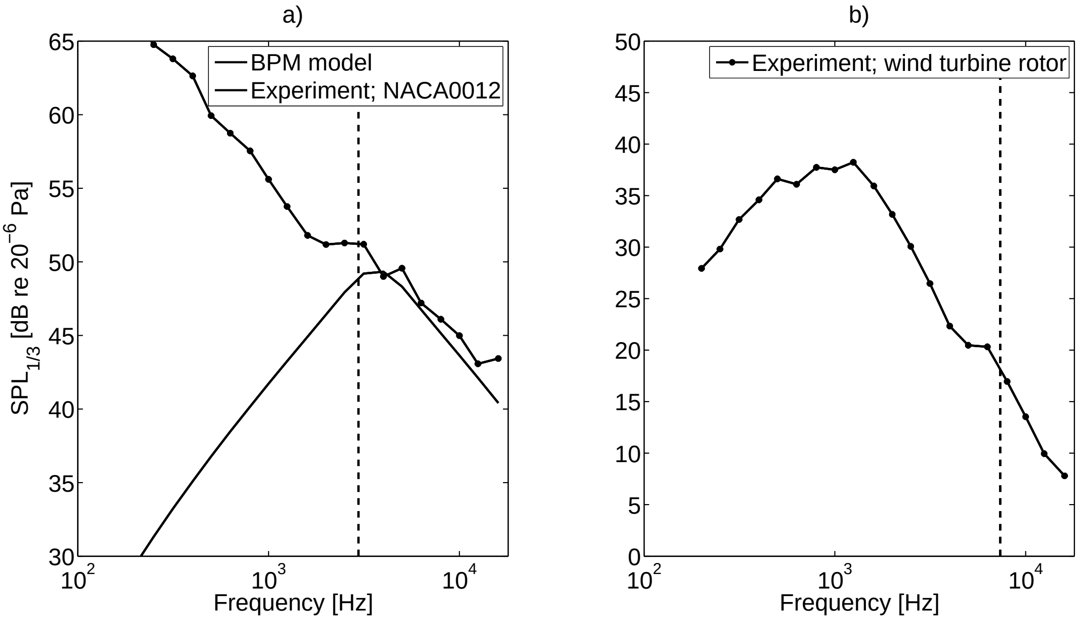

Figure 5: a) One third octave band sound pressure level at R = 0.055 and $\Theta = 85^\circ$ for a stationary NACA0012 blade (see figure 2), b) One-third octave band sound pressure level at 90° microphone position for the wind turbine rotor. The dotted vertical line on both figures indicates $St = 0.069$.

Good agreement between the BPM model and the measurements is observed for $St > 0.1$ in figure 5a. This means that trailing edge noise emissions from the tripped NACA0012 blade are as expected. The presence of a "low frequency" peak is observed at trailing edge peak radiating frequency of ∼3 kHz and the associated Strouhal number is 0.069. Doolan and Moreau [4] believe that this is a true characteristic of trailing edge noise and thus deserves attention since it contains a significant amount of energy in the audible frequency range.

A "low frequency" trailing edge peak is also present in figure 5b, at ∼7 kHz. However, the peak in that case does not correspond to St = 0.069, as can be seen. Reasons for this discrepancy could be; underestimation of the boundary layer thickness by the BPM empirical formulation, rotational effects or tip vortex interference.

Since the "low frequency" peak is observed in both facilities, the facility effect can be excluded. Further investigation is necessary in order to obtain more information about the the nature of the trailing edge noise on a rotating airfoil, in particular the nature of "low frequency" peak.

In figure 7 the broadband power spectral densities for two tower clearances; d = 20 mm and d = 70 mm are shown. The effect of the tower on the sound emissions is clearly visible in the low frequency range which is the range of blade tower interaction noise. In this range, the magnitude of the upper harmonics of the blade pass frequency magnitude is up to 20 dB different for the two clearance distances. This is due to the change in the aerodynamic force acting on the blade when the blade is passing the tower, meaning that the blade streamlines are displaced due to the tower presence. At higher frequencies, between 2 kHz and 5 kHz, the difference between the two clearance distances is also significant. The PSD of d = 70 mm is higher compared to d = 20 mm in the frequency range between 1.6 kHz and 4.2 kHz. This is as expected since the tower (70 mm in diameter) at these frequencies becomes acoustically significant and thus causes acoustic scattering which consequently causes the increase in sound pressure. The scattering is furthermore illustrated in figure 6 as a function of angle.

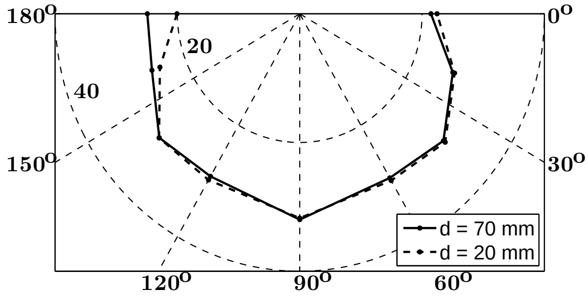

Figure 6: Directivity function at 2064 Hz for d = 20 mm and d = 70 mm.

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Figure 6 shows a significant increase in magnitude occurring on one side of the wind turbine rotor due to the cardioid directivity of the airfoil self-noise in that frequency range. As observed, acoustic scattering can have a significant effect on the sound field in close proximity to the wind turbine rotor and it is therefore believed that this could also be the case for large wind turbines.

In order to gain a better understanding of blade tower interaction noise, further experiments will include the measurement of aerodynamic pressure fluctuations on both sides of the blade tip and tower simultaneously. These measurements will also be carried out under more realistic operating conditions including an angle of attack $> 0°$.

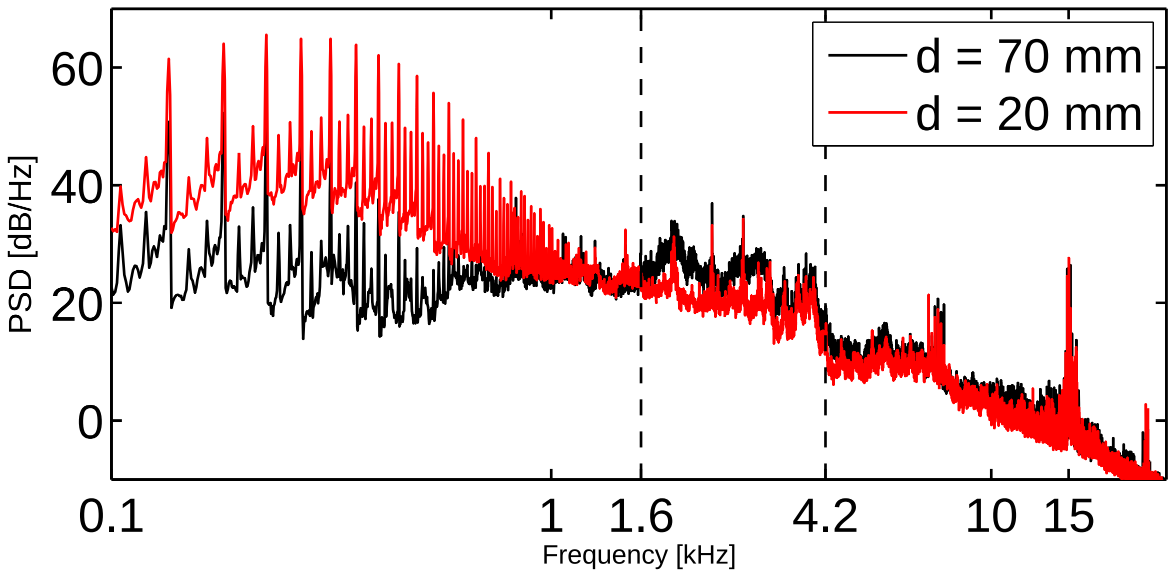

Figure 7: Power spectral density (PSD) at 180° microphone position for tower clearances of d = 70 mm and d = 20 mm.

Conclusions

Preliminary results from the anechoic wind tunnel and the anechoic chamber are encouraging since similar noise features have been identified. The single rotor blade trailing edge noise measured in the wind tunnel shows the presence of the "low frequency" peak. The "low frequency" peak is also present in the wind turbine rotor noise measurements. However, since the peaks do not occur at the same Strouhal number they cannot be attributed to the same noise production mechanism with great certainty. Further measurements will be conducted in order to resolve the origin of the peak.

Measurements in the anechoic chamber show that the presence of a tower has a significant influence on the aerodynamic noise emissions via aerodynamic loading and acoustic scattering phenomena. Further investigation is needed in order to fully understand the scattering phenomena outlined in this paper.

Acknowledgements

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