Effect of rotational harmonics on sound power from HAWT blades

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DOI: 10.13111/2066-8201.2025.17.4.24

Received: 26 October 2025/ Accepted: 16 November 2025/ Published: December 2025

Abstract: *With rising greenhouse gas emissions and increasing energy demands across the globe, sustainable energy production has become essential today. Even though wind turbines help mitigate the harmful emissions, the HAWT blades are one of the key sources of aerodynamic noise and are designed to provide long term energy production. In this work we demonstrate the impact of rotational harmonics, turbine tilt angle on sound power level from HAWT blades during operation. At mean wind speed of 8 m/s the change in downward tilt angle of more than 5 deg increases the sound power level by 5 dB. Predominant noise occurred mainly from trailing edge regions of blade which suggests that number of blades in turbine, wind velocity profile and position of tilt angle significantly influenced on sound power level from wind turbine blad*es.

Key Words: *Wind Turbine, Blade, Turbulent Boundary Layer, Sound Pressure, Wind Velocity Profile, Aerodynamic Noise*

1. INTRODUCTION

In the recent past the world has witnessed an unprecedented increase in the use of renewable energy resources with large scale power plant installations to curb harmful CO_2 emissions and protect the environment from climate change activities. Among renewable energy sources, wind energy has attracted much attention compared to solar systems and even the coal-based energy sources due to its operating efficiency, low cost of energy and cleaner production of electricity. When wind turbines grew bigger in size, noise from moving blades has become critical objectives in wind turbine airfoil design to achieve greater efficiency.

From the perspective of social acceptance, the noise aspect becomes very important particular for onshore turbines, such that low-noise wind turbine design is an important parameter. Hence a detailed understanding airfoil noise generation mechanism is essential to make energy extraction more efficient.

The wind turbine noise regulation across different countries is based on inhabitants and in Europe stringent laws related to noise levels are applied. Particularly, the noise perceived from rotating blades of wind turbines are believed to radiate a cyclical pattern of sound waves which manifest as impulse or broadband aerodynamic noise. [1] conducted a series of surveys in a field measurement campaign on how infrasonic and low frequency wind farm noise is perceived in rural areas both indoors and outdoors of houses.

Noise measuring instruments and locations are selected based on the dose-response study which is useful for determining the suitable noise limits. An investigation performed on the masking potential of ambient background noise levels during nighttime and daytime based on NZS 6808:2010 and SA (2009) EPA noise guidelines as well as ISO 9613-2 regulation.

For many horizontal axis wind turbines, the number of blades and rotational speed in a rotor influence rotational harmonics and subsequent infrasonic, low frequency aerodynamic noise emissions from blades.

The objective of the present work, is to investigate the extent of noise emissions that result from rotational harmonics as well as the influence of turbine design parameter variation on the overall aerodynamic sound level emitted from the blades.

2. METHODOLOGY

The wind turbines operating in open environments exhibit amplitude modulation of sound pressure level at blade passing frequencies which means the number of blades play an integral role in rotational harmonics in overall noise level perceived by inhabitants near wind turbines.

[2] have investigated amplitude modulation for two and three-bladed large-scale wind turbines. The broadband SPL spectrum for downwind and upwind turbine rotors in low and mid-band frequency range between 20 Hz and 2 kHz was computed based on the analytical closed form solutions for predicting rotational noise from helicopter rotors.

According to this method, to predict near field flow induced noise at higher harmonics an empirical relation was derived as function of tip speed and swept area of rotor. However for predicting far field noise, Lowson's work on unsteady rotor blade loading of turbine torque and thrust derived using complex Fourier coefficients given by Eq. 8b in [3] was implemented. The SPL modulation amplitudes varied over time scales for a single rotor revolution measured at 150 m and 183 m distance from the source. The downstream rotor had a diameter of 79 m, while the upstream rotor had a diameter of 92 m. It was found that the amplitude of the SPL acoustic pressure signals measured from the upstream rotor varies cyclically, with high amplitudes and a phase difference of 180°, when the blades pass by the tower, compared to the downstream rotor when the blades pass by the tower.

Further, intermittent SPL peaks were found at frequencies above 600 Hz and below 1.2 kHz, which are believed to be caused by noise from the gearbox or cooling fan inside the nacelle of the turbine.

Additionally, observing the broadband rotational harmonics noise spectrum at infrasonic and low frequencies for downwind and upwind rotors for $f < 20$ Hz, it can be seen that the rotating harmonics of the turbine rotor in the SPL spectra are stronger for downwind rotors than for upwind upwind rotors.

However, for both upwind and downwind rotors the in the case of upwind rotors, generator shaft harmonics are were found to emit tonal noise peaks at high frequencies and that varied with integral multiples of blade passing frequencies [2].

It can be noted that rotational harmonics are a function of integral multiples of blade passing frequency which result in radiation of acoustic pulses in far field. The acoustic pulses are attributed to unsteady blade loads due to rapid changes in the lift and drag forces over the blade surface in rotor plane.

This variation in blade loading was computed using the Sears function in terms of complex Fourier coefficients which considers the sinusoidal gusts in wind field. A generalized expression for RMS sound pressure level for upwind and downwind rotors proposed by [4] is given by Eq. 1.

$$P_{rms,\,n}=\frac{\sqrt{2}\sin\gamma}{4\pi R_e d}M_n^2\sum_m e^{im(\emptyset-\frac{\pi}{2})}J_x\left(a_m^T\cos\gamma-\frac{nB-m}{M_n}a_m^Q\right) \quad (1)$$

where $M_n = nB\frac{R_e\Omega}{a_o}$, m is the blade loading harmonic index, n is the sound pressure harmonic, $P_{rms,n}$ is the rms sound pressure for nth harmonic, B is the number of blades, Ω is rotor speed in rpm, c is the speed of sound, J_x is the Bessel function of first kind and order x, R_e is the effective blade radius, d is distance from rotor hub, Υ is the blade azimuth angle, ϕ is the altitude angle to receiver, and are the complex Fourier coefficients for thrust and torque acting on the turbine rotor [2, 3].

3. RESULTS

Rotational Harmonics

Fig. 1 demonstrates the comparison of sound pressure level varying with harmonic number, n computed at frequency resolution, Δf value of 0.25 Hz, following the [4] approach.

It can be observed that for three-bladed turbines, peaks at low frequencies are closely spaced showing a logarithmic decrease in pressure amplitudes and agree well with experiment data of [2].As the frequency increases, the peaks are spaced wider apart with reduction in amplitudes which are found to deviate with experiment data by more than 5%.

However, for two-bladed turbines, sound pressure peaks appear equidistant for integral multiples of blade passing frequencies.

Also, it may be noted that noise radiated in rotor plane shows a strong correlation with strength of wake produced downstream of tower and is known as blade tower interaction (BTI) reinforcement., particularly when the turbine is operating in large array of wind farms. This phenomenon occurs predominantly in downwind turbines compared to upwind turbines of similar size,and tends to increase the sound pressure level by 3–6 dB.

A similar effect of amplitude modulation known as swish reinforcement is observed from the trailing edge of blade surface.

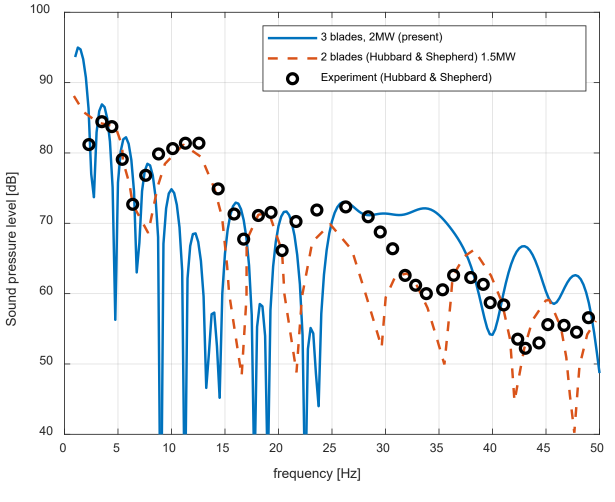
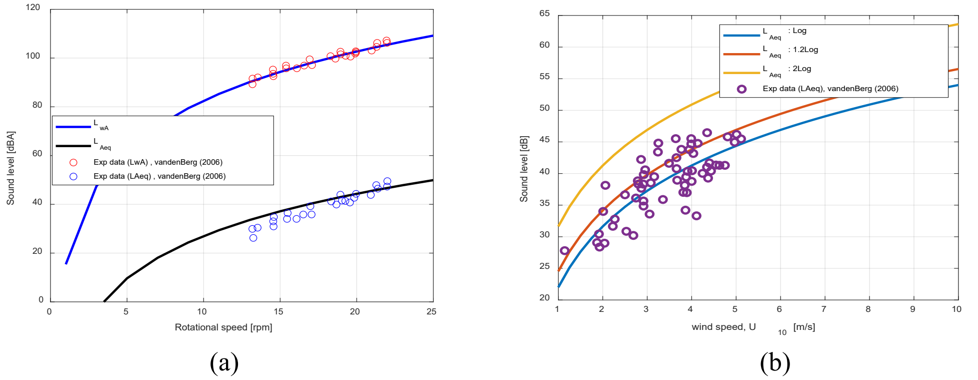


Figure 1. Illustration of sound pressure level varying with harmonic number, *n,* at wind speed of 13.5 m/s compared to experiment data measured downwind at distance of ~100m for (Δf = 0.25Hz)

Wind Velocity Profile Type and Tilt Angle

In an experiment study by [5] it was found that sound levels from wind farms for different microphone configurations were influenced by atmospheric stability patterns during nighttime and daytimes which is one of key determinants of velocity profiles as well as fundamental nature of wind turbine noise. Further it explains the beating nature of sound termed as *swish* to help understand the behavior of wind turbine noise influenced by atmospheric turbulence and atmospheric stability patterns. An investigation based on turbine design parameters such as tilt angle has been done to correlate with sound pressure levels. Furthermore, relationship between microphone screen diameter, mean wind velocity and atmospheric parameters has been assessed to quantify the possible errors due to presence of microphone screen in measurement of sound pressure level and validated results under different atmospheric stability conditions. Fig. 2a and Fig. 2b show that L_{wA} and L_{Aeq} sound levels from a 3 bladed turbine for varying rotational speed and wind speeds agreed well with experiment data. The sound levels were estimated based on Eq. 4.4 given in [5] which demonstrates a difference of 57.9 dBA between L_{Aeq} and L_{wA}. It can be noted that L_{Aeq} sound levels predicted using standard and 20% higher logarithmic velocity profile agree within 5% of experiment data compared to 100% rise in standard logarithmic velocity profile [5]. Most wind turbine blades are subjected to damage over their lifetime and turbine manufacturers use damage detection techniques to analyze the acoustic emission process from the leading or trailing edge of the blades [6]. The damage severity and occurrence level varies from one site location to another. Additionally, the turbulent boundary layer trailing edge mechanism is one of the important sources of aerodynamic noise generation from blades. To a large extent the aerodynamic flow conditions influence this mechanism however, the type of velocity profile prevailing at a given site would also impact the local shear on rototating blades and increase the noise levels [7, 8].
A recent study by [9] shows that the position of the rotor pitch angle affects the sound levels generated by the blades and is caused by changes in the angle of attack of the blades.

This change alters the unsteady aerodynamic lift forces and turbulent flow patterns of the turbulent boundary layer on blades [10]. It can be mentioned that an increase of upward inclination (tilt) by more than 5^0 with respect to horizontal plane would increase trailing edge noise levels from blades by 5 dB. In contrast, the downward inclination increase by 5^0 tends reduce noise emission levels by 1.5 dB.



(a) (b)

Figure 2 Comparison of (a) sound pressure (L_{Aeq}) and power (L_w) level difference with experiment data of [5] for different rotational speeds of three bladed turbine (b) sound pressure (L_{Aeq}) predicted using *1x, 1.2x* and *2x* logarithmic velocity profile expressions for different wind speeds with experiment data of [5]

4. CONCLUSIONS

The present study demonstrates that rotational harmonics from a wind turbine vary as function of blade passing frequencies. They are found to produce more intermittent high peaks at infrasonic (< 10 Hz) and low frequencies (20 Hz < f < 50 Hz) but attenuate as frequencies increase above 50 Hz in case of 3 blade turbine compared to 2 bladed machine. The sound levels also vary with type of velocity profiles and prevailing mean wind speeds. The sound pressure levels increased by 8 to 10 dB with increase in effective logarithmic velocity profile at a given mean wind speed.

REFERENCES

[1] K. Hansen, N. Henrys, C. Hansen, C. Doolan, D. Moreau, Wind farm noise – what is a reasonable limit in rural areas ?, *Proceedings of acoustics 2012* – Fremantle, Australia, 2012

[2] H. H. Hubbard, K. P. Shephard, Aeroacoustics of large wind turbines, *J. Acoustical Society of America*, vol **89**, pp 2495 – 2508, 1991.

[3] M. V. Lowson, Theoretical analysis of compressor noise, *J. Acoustical Society of America*, vol **47**, pp 371-385, 1970.

[4] J. Viterna, *The NASA LeRC wind turbine sound prediction code*, 2nd DOE/NASA wind turbine dynamics workshop, Report no: TM-81737 /20366-1, 1981.

[5] P. Van den Berg, *The sound of high winds: the effect of atmospheric stability on wind turbine sound and microphone noise*, Doctoral thesis, University of Groningen, Netherlands, 2006.

[6] Y. Zhang, F. Avallone, S. Watson, An aero-acoustic based approach for wind turbine blade damage detection, The science of making torque from wind, TORQUE, *J. Physics Conference Series*, IOP publishing, 2022, doi:10.1088/1742-6596/2265/2/022088.

[7] V. Bhargava, R. Samala, Effect of boundary layer on broadband noise from wind turbine blades, *J. Aerospace Technology and Management*, 2019, https://doi.org/10.5028/jatm.v11.1045

[8] V. B. Nukala, C. P. Padhy, Influence of Wind Velocity Profile on Broadband Noise Emissions from Wind Turbine Blades Under Neutral Atmospheric Conditions, *Romanian Journal of Acoustics and Vibration*, vol **21**, no 1, pp. 20–26, 2024.

[9] F. Van den Berg, E. Koppen, J. Boon, M. E. Smink, Development of Sound Power of Onshore Wind Turbines including its Spectral Distribution, *Sound & Vibration*, vol **59**, no 1, 2025.

[10] V. Bhargava, S. P. Maddula, S. N. Venkata Neigapula, Md. Akhtar Khan, C. P. Padhy, Y. D. Dwivedi, Aerodynamic flow modelling of NACA 0010 using 2D panel and Jukouwski methods, *Aircraft engineering and aerospace technology,* vol **94,** no 6, 2022.