Aeroacoustic Noise Produced from Novel Wind Turbine Rotor Design for Small-scale Applications in Sri Lanka

Udara Herat Bandara & Malika Perera
Sri Lanka Institute of Information Technology
New Kandy Road, Malabe 10115, Sri Lanka.
malika.p@sliit.lk, udaraherat@gmail.com

ABSTRACT

Growing concerns regarding non-renewable energy sources have driven academic and industrial scholars as well as global superpowers to seek sustainable, greener power generation alternatives. One such prominent renewable substitute is wind power which was initially utilized in harnessing electricity towards the late nineteenth century though archaeological evidence has proved that wind power had been employed for various purposes since predynastic Egypt. Extensive research and development has enabled the efficient operation of multi megawatt wind farms at present though inherent drawbacks still persist, of which aerodynamic noise, also referred to as aeroacoustic noise, is of major concern. This paper details the simulative investigation of the aeroacoustic sound levels produced by an optimized novel wind turbine design intended for the use in small scale applications with medium wind speed conditions in Sri Lanka, using ANSYS Fluent. A transient analysis using the Shear Stress Transport turbulence model was used to obtain the converged pressure fluctuations which subsequently revealed the sound pressure levels via Fast Fourier Transforms at six predetermined locations of interest. The results revealed the presence of acoustic vibrations within the Infrasonic and Low Frequency Noise range with sound pressure levels exceeding one hundred decibels, particularly up to a frequency of twenty five Hertz. Prolonged exposure to elevated levels of low frequency noise has been identified to cause severe discomfort to humans though further conclusive research is required. Finer mesh controls which incorporate minute boundary layer variations during motion and precisely encapsulate the turbine geometry could further improve the accuracy of the results, however this would require adequate computational capacity. The results of this research primarily serve as a basis for identifying possible improvements for the novel rotor design in addition to providing a comparative study for future research, both simulative and empirical, on the aerodynamic noise emissions associated with wind turbines.

KEYWORDS: *Aerodynamic Noise, Wind Turbine, Infrasonic and Low Frequency Noise, ANSYS Simulation*

1 INTRODUCTION

The concept of generating electricity from wind power was successfully implemented only during the 19^{th} century, though wind power had been utilized by mankind from as far back as the predynastic era of Egypt (U.S. Energy Information Administration, 2021). Grain milling - which coined the term windmill, water pumping - as seen mainly in The Netherlands and America among others and sailing were the three most prominent applications of wind power prior to the 19^{th} century, after which however, the term wind turbine quickly replaced and far exceeded the use of the term windmill. As with all mechanical applications, the use of wind power also has its inherent limitations and drawbacks. one of the most prominent of which is the noise concerns. Wind turbine noise can be attributed to two main contributors: Mechanical and Aerodynamic noise.

Mechanical noise commonly refers to the undesired acoustic vibrations generated through the interactions of numerous mechanical components, as the name suggests, such like gears, shafts and other fixtures present within the nacelle of the turbine. The noise produced thus has been further identified to be amplified within the tower (Stauber, Marmo, & Black, 2017). However, through

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extensive research and development over the years, mechanical noise of wind turbines has been almost completely mitigated via damping mechanisms and active noise control methods (Lee, et al., 2021). Aerodynamic noise though, is still persistent and the intrinsic complexities of the sources of aerodynamic noise create difficulties in modeling and assessing it. Ongoing research, particularly on Computer Aided Aeroacoustics (CAA), aim to provide a better understanding of the occurrence and propagation of aerodynamic noise which in turn will allow novel mitigation techniques and more efficient control measures to be developed (Jianu, Rosen, & Naterer, 2012). In addition to devising noise controlling mechanisms there is also heightened focus on improving performance characteristics and developing application specific wind turbine models.

One such novel development is a simplified optimized rotor designed for small-scale applications in Sri Lanka which was the brainchild of Sugathapala, et al. (2020). The current study expands on the said study by simulative analysis of the aeroacoustic noise levels produced by the novel three bladed rotor design, intended for an upwind application in medium wind speed conditions. The blades of the said rotor design used a National Advisory Committee for Aeronautics (NACA) 4412 airfoil and consisted of a constant chord length and pitch angle with a design tip speed ratio of five. Proportionate dimensions have been used for the hub within the context of this study and Table 1 summarizes the details and dimensions while Figure 1 shows a depiction of the rotor used for this study.

Table 1: Details and Dimensions of Optimized Novel Rotor Design Used

PARAMETER	VALUE
Airfoil used	NACA 4412
Chord length	0.13 m (constant)
Pitch Angle	7^{o} (constant)
Radius	1.326 m
Number of Blades	3
Tip Speed Ratio	5
Hub Diameter	0.432 m
Hub Length	0.360 m
Wind Speed (average medium condition)	5 m/s
Wind Turbine Orientation	Upwind

This study therefore, mainly aims to assess the aerodynamic noise based Sound Pressure Levels (SPLs) produced by the novel wind turbine rotor design of Sugathapala, et al. (2020) and to identify whether significant levels of infrasonic and low frequency noise levels are produced. Furthermore the results of this study could serve as a basis for refined expansion on the topic of aerodynamic noise generated from small-scale application type wind turbines. In addition, this study contributes to improving the extant deficiency of scientific ventures particularly in Sri Lanka, that are based on wind turbines and associated aerodynamic noise.

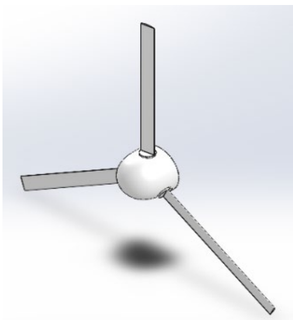
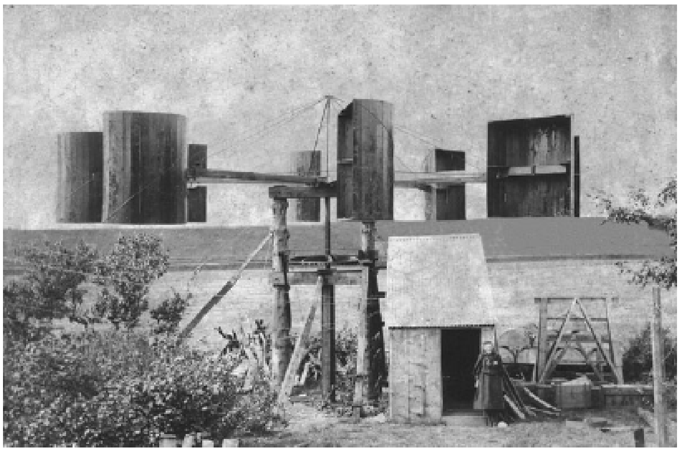


Figure 1: Depiction of novel rotor design used in simulating aerodynamic noise levels

2 BACKGROUND

The first known wind turbine was invented by Professor James Blyth, a Scottish academic who used a large vertical axis wind turbine design that had four hemispherical cups mounted on extended metal arms (Price 2005). This wind turbine relied on the wind drag to operate, similar to the drag based Panemone windmills of ancient Persia (Shepherd 1990). The American entrepreneur Charles Francis Brush is credited with the invention of the first lift based horizontal axis wind turbine with working principles much like that of modern wind turbines. He built an enormous wooden wind turbine with a rotor diameter of more than fifty feet, that successfully powered his home for an estimated twenty years (Righter, 1996; Allerhand, 2021).



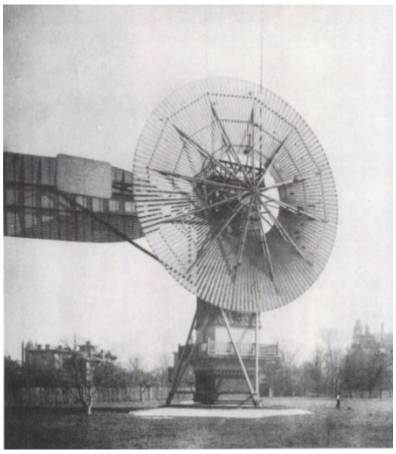


Figure 2: Professor Blyth's wind turbine (*left*) (Price, 2005) and Brush's wind turbine (*right*) (Righter, 1996). Note the human figures standing in the foreground of each picture for a size comparison.

Though these initial wind turbines were successful in generating electricity, the respective efficiencies were low with the Brush turbine identified to have generated only a meagre 12 kilowatts of energy (Tong, 2010). Extensive research, which also included some of the first ever wind tunnel tests, conducted by the Danish Poul La Cour led to a revolutionary refinement of wind turbine designs. He suggested that a large number of blades were unnecessary for optimal performance which subsequently led to the classic three bladed rotor designs for horizontal axis wind turbines, which is still the accepted norm. La Cour further invented the *kratostat*, a device which regulated the erratic changes in the rotational speed of the turbine drive shaft so that a steady output can be obtained (Pedersen, 2010; Powell, 1910), which was fundamental to the success of the initial wind turbine designs and published his findings in the form of a book named "*Forsøgsmøllen*" which is the Danish translation of "The Test Turbine" in 1900.

The initiation by La Cour followed by the period of extensive research and development during and after the Second World War by notable scientists like Albert Betz – who theorized that the maximum efficiency of a lift based wind turbine cannot exceed 59.3%, popularly known as Betz's Limit (Hau, 2006) – in addition to growing concerns over usage of fossil fuels and environmental harm, established the sustainable concept of wind powered electricity generation in most parts of the world. Within a relatively short time span wind turbines had evolved from meagre kilowatt generating dwarfs to megawatt generating giants that can be erected both onshore and offshore. At present, a significant proportion of the electricity demand of many countries like Denmark is supplied by windfarms capable of generating multi-megawatts of power (Lee and Zhao 2021), though aerodynamic noise impacts still persist.

Due to the inherent complexities of aerodynamic noise sources, purely analytical models prove difficult, if not impossible to build. Therefore, semi-empirical, semi-analytical models and derived results are used when modelling aerodynamic noise, particularly from wind turbines (Brooks, et al. 1989).

2.1 Aerodynamic Noise Sources

The sources of aerodynamic noise with reference to a wind turbine can be mainly categorized into two: 1) self-noise that arises due to the geometry and characteristics of the airfoil utilized and 2) turbulence inflow which is caused due to atmospheric turbulence present in the oncoming wind (Sørensen 2012). There are several sources of self-noise of a wind turbine namely: 1) turbulent boundary layer trailing edge noise, 2) separation-stall noise, 3) laminar boundary layer vortex shedding noise, 4) tip vortex formation noise and 5) trailing edge bluntness vortex shedding noise (Brooks, Pope, & Marcolini, 1989).

2.2 Infrasonic and Low Frequency Noise (ILFN)

Wind turbines are notorious producers of low frequency acoustic vibrations, however there is a deficiency in the number of academic ventures that aim to assess the exact levels of low frequency noise produced thus (Hansen & Hansen, 2020). The frequency range sensitive to humans with unimpaired hearing averages between 20 to 20,000 Hertz and is known as the auditory or sonic region. Frequencies exceeding 20,000 Hertz are categorized as the Ultrasonic region whereas the region below 20 Hertz is defined as the infrasonic region (Bies, Hansen, & Howard, 2018). There is no absolute upper boundary to the range of low frequency vibrations, however frequencies below 100 Hertz are usually considered as low frequency though some research have used frequencies below 200 Hertz as well. With respect to the context of the current study, frequencies below 100 Hertz have been considered as low frequency.

Several researches have been conducted on the effects of low frequency and infrasonic vibrations on humans and the respective findings have revealed that prolonged exposure to ILFN resulted in severe to acute discomfort in humans and that physical manifestations could also occur in the form of nausea, sleep disorders and Vibroacoustic Disease (VAD) according to the individual sensitivities of the effected (Leventhall 2009). However, the results are yet to be confirmed as entirely conclusive.

2.3 k-omega Shear Stress Transport Viscous Model

The k-omega SST turbulence model belongs to the class of hybrid Reynolds Averaged Navier Stokes (RANS) turbulence models that govern fluid flow with all the turbulent effects included (SIMSCALE 2021), (AutoDesk 2019). This model was developed by Florian Menter in order to minimize the errors present in the k-epsilon and k-omega models (Menter 1994). It is referred to as a hybrid model since it combines two other turbulence models namely; the Wilcox k-omega and k-epsilon models. This makes the k-omega SST model better suited for modeling flows around airfoils (ANSYS, Inc. 2021).

In addition to the conservation equations, the k-omega SST model contains two partial differential equations that govern the transport of two variables namely; the turbulent kinetic energy (k) and the specific turbulent dissipation rate (omega) (SIMSCALE 2021). Further modifications have been done which make it a reliable model to predict the behavior of viscous flows with low Reynolds numbers in particular, although inherent limitations exist (Versteeg and Malalasekera 2007).

2.4 Ffowcs-Williams and Hawkings (FW-H) Acoustic Model

As the name of the model indicates, it was developed by John "Shôn" Eirwyn Ffowcs Williams, an Emeritus Professor at the University of Cambridge and one of his fellow students David Hawkings (Ffowcs Williams and Hawkings 1969). This acoustic model is an inhomogeneous wave equation derived by a combination of the continuity and Navier-Stokes equations and can be used to accurately predict mid-field to far-field acoustics (ANSYS, Inc. 2021).

3 PROCEDURE

3.1 Simulation

The aeroacoustic noise levels produced by the novel turbine design were simulated using ANSYS Fluent software. A transient analysis with 1500 time steps and time step size of 0.01 was conducted using the k-omega SST viscous model to simulate the flow characteristics while the acoustic pressure fluctuations at the six receiver locations of interest were obtained using the FW-H model. The pressure fluctuations thus obtained were used to derive the Sound Pressure Levels (SPLs) at the respective receiver locations using Fast Fourier Transforms.

The geometries of the rotating domain which include the turbine, modeled to actual size, were created using Solidworks while the stationary domain which was used to model the envelope of air flow across the turbine was created using ANSYS SpaceClaim so that the contact surfaces between the two domains were generated automatically. A velocity inlet of 5 m/s and a pressure outlet of zero gauge pressure were assigned to the stationary domain as shown in Figure 3 while the turbine and all other surfaces excluding the contact surfaces - which were assigned as interfaces - were considered as stationary walls.

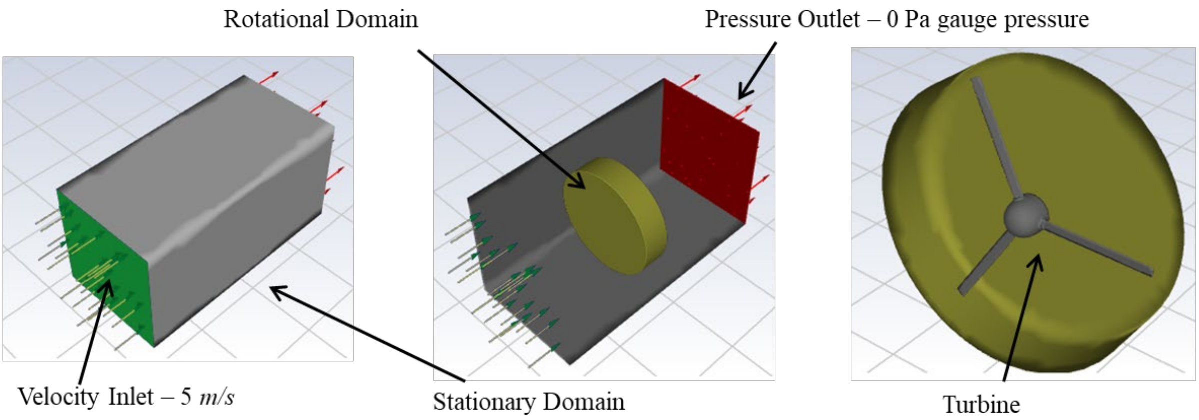


Figure 3: Rotational and Stationary Domain and Boundary Conditions Used in the Simulation

The overall mesh of the actual sized rotor of the wind turbine contained 184,347 nodes and a total of 949,865 tetrahedral elements, all of which followed a linear order. The wind turbine geometry was meshed with a general sizing of 30mm while the maximum element size was set to 500mm without enabling the adaptive sizing function. All mesh components less than 0.15mm in size were set to be defeatured. Patch conforming tetrahedron elements were used for the rotational geometry of the model. An inflation setting containing four layers at a smooth transition and a growth rate of 1.2 was applied to the wind turbine geometry only.

Nine faces of the peripheral geometry – bounding cuboid and cylindrical periphery – were meshed using an element size of 360mm and a defeatured limit of 0.24mm. This was done to minimize the number of elements and reduce the overall complexity of the mesh. A default growth rate of 1.2 was used with the Influence Volume function set to No. The peripheral mesh was further customized to capture the proximity of both faces and edges with a minimum size setting of 0.6mm and the default value of 3 cells across a gap. However, the capture curvature function was set to No in order to stay within the boundaries of the available computational capacity.

3.2 Receiver Locations

The Sound Pressure Levels from six receiver positions were obtained in order to identify the aeroacoustic noise produced from this wind turbine model. Two of the receiver locations were positioned 0.5m in front and to the rear of the rotor while the other four were positioned on the vertical plane passing through the center of the airfoil chord. These four receivers were located on the top, bottom, left and right extremities of an imaginary circle which was concentric to the rotor, having radius equal to half the blade length.

4 RESULTS AND DISCUSSION

Convergence of the simulation was established by using residual monitoring as well as from a user defined parameter which monitored the moment generated by the turbine. The simulation results revealed that aeroacoustic noise below 50 Hertz was present with tonal peaks corresponding to the harmonics of the blade pass frequency of the wind turbine. These peaks indicated high SPLs with several exceeding 100 decibels. This is indicative of high levels of acoustic vibrations that fall into the category of infrasonic and low frequency noise. The four receiver locations on the rotating plane of the rotor, displayed frequency spectra with notable similarities observed amongst the four receivers but indicated clear differences with the spectra corresponding to the other two locations as seen in Figure 4. A marked reduction in the SPLs of the receivers before and beyond the rotor can be identified with a greater reduction seen in the SPL of the receiver location in front of the rotor. Even though the SPL trends downwards however, tonal effects might persist as seen by the spike in amplitudes corresponding to the blade pass frequency harmonics.

In addition to the continuous frequency spectra, sound pressure levels according to octave bands of the receiver location on the right of the rotating plane of the rotor as shown in Figure 5, further indicate that the novel turbine design produced significantly high levels of infrasonic and low frequency acoustic vibrations due to aerodynamic interactions. Only the receiver on the right has been considered since it corresponds to the highest peaks in the SPL as seen in Figure 4. It is evident from the octave band frequency spectrum that a larger SPL is present towards the lower end of the spectrum. This can be interpreted as an indication of the presence of high levels of infrasonic and low frequency noise which are produced by the blade interactions with the wind which is at a steady speed of 5 m/s.

Since the receiver locations that are 0.5m away from the rotor indicate reductions in the respective SPLs as the distance from the rotor to the receiver increases, the ambient noise present might mask the noise produced by the rotor. However due to the presence of tonality, the subsequent characteristic effects could still persist at varied distances from the rotor. This could cause disturbance, varying from mild to severe in nature, to the residents in the vicinity who are subjected to prolonged continuous exposure in addition to distressing the fauna present.

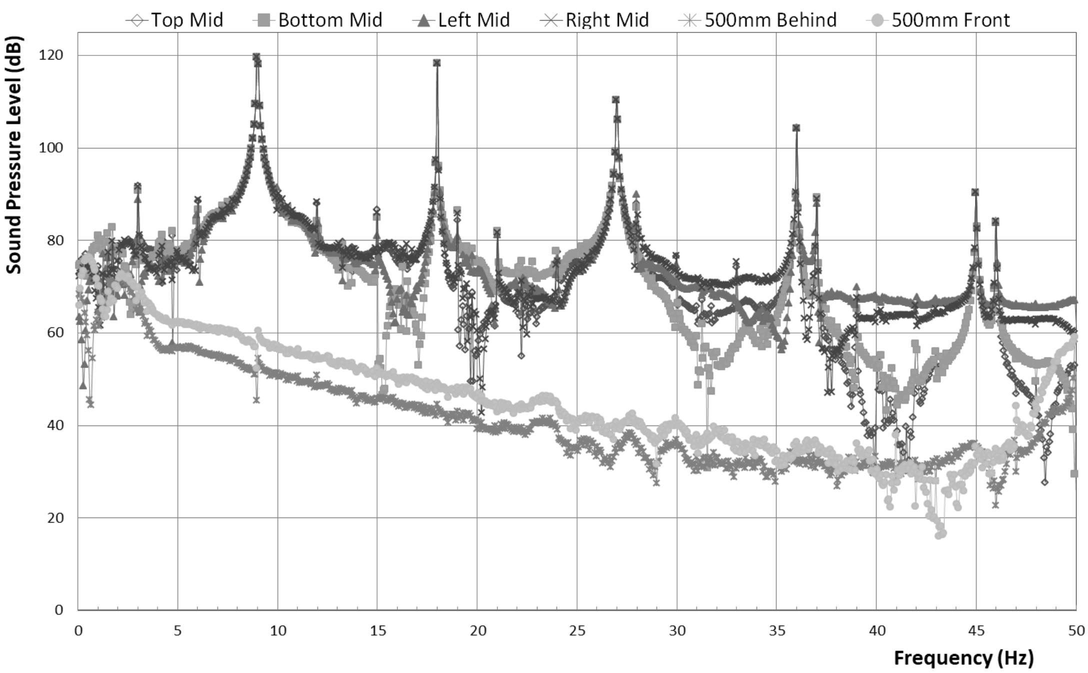


Figure 4: Spectra of Sound Pressure Levels of the Six Receiver Locations of the

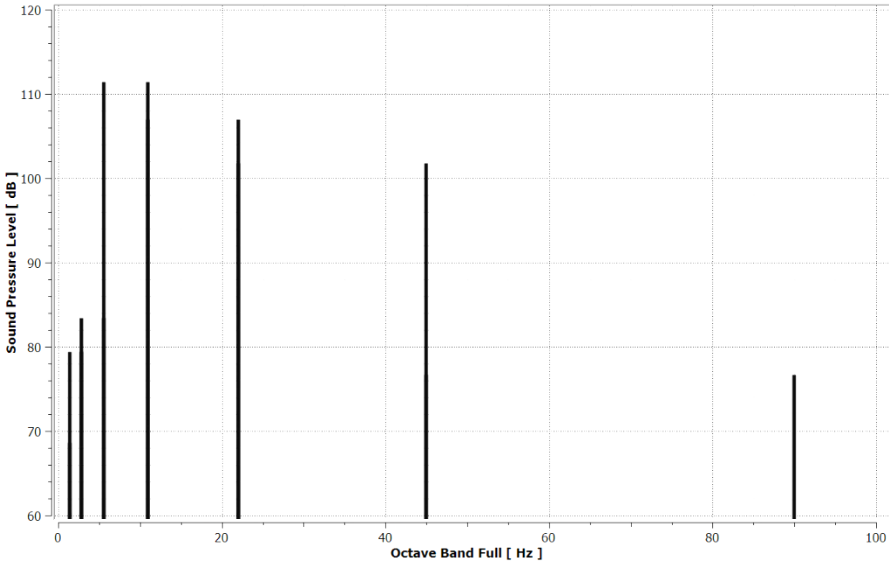


Figure 5: Octave Band Sound Pressure Levels of the receiver location on the right of the rotating plane

In light of this it can be surmised that the novel rotor design might not be ideally suited for use in densely populated areas due to the high levels of tonal ILFN produced. Though the SPL tends to decrease within a short radius from the rotor, tonal effects present, could still cause discomforts to individuals in the vicinity. Particularly sensitive individuals might even display severely adverse effects in the form of nausea or VAD.

5 CONCLUSIONS

The aeroacoustic noise emissions of a novel horizontal axis wind turbine design for small scale applications in Sri Lanka were investigated for the medium wind speed condition of 5 m/s using a simulation in ANSYS Fluent. Aeroacoustic noise up to a frequency of 50 Hertz was identified to be produced along with tonal peaks exceeding sound pressure levels of 100 decibels corresponding to harmonics of the blade pass frequency. Therefore, it is advisable to refrain from operating the novel wind turbine design in densely populated areas due to potential discomforts which may arise upon prolonged exposure to the infrasonic and low frequency noise emitted from this wind turbine design. Further research using mesh refinements and precise parameters can be used to derive a more realistic simulation though this would require machines with considerable computational capacity. Additionally performance enhancements as well as noise reduction and mitigation methods for the novel rotor design utilized within this study could be designed and developed and the subsequent effectiveness could be gauged by comparison with the current results.

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