Experimental Aeroacoustics Analysis of Vertical Axis Wind Turbine

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Declaration

I certify that this research work titled "*Experimental Aeroacoustics Analysis of Vertical Axis Wind Turbine"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Abstract

Wind energy is one of the rich and clean renewable resources to deal with energy crises and global warming. Mainstreaming of this form of energy has produced the possibility of making wind turbines a part of the urban landscape. The noise from the vertical axis wind turbine (VAWT) is the main issue. Therefore, it is essential to analyze the parameters which can help to reduce noise. The aerodynamic performance of a VAWT has been significantly improved by efficient blade design and with different arrangements of blades. In this work, a new design of VAWTs is present for the reduction of noise generation. This study focuses on measuring acoustic signals on a 3-bladed VAWT in a nonresonant chamber at different TSR (tip speed ratio) using a microphonic array. In biplane and tandem VAWT every blade is constructed using two airfoils. In this work blade with different spacing has been studied. The SPL results of the spectrum of VAWT inferred that tonal noises such as blade passing frequencies are leading at lower frequencies whereas broadband noise harmonizes to all distinct ranges of frequencies. The result of the spacing between the blades shows that in biplane VAWT 21% and in tandem 60% is the best arrangement for noise reduction. Also, the major portion of noise from the source is influenced by aerodynamic noises generated due to flow separation.

Key Words: *Wind Energy, VAWT, Biplane, Tandem, SPL, Tonal, Broadband, Nonresonant Chamber*.

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Symbols

p	Air pressure
σ	Solidity
P_m	Spectrum m microphone
R_0	Rotor radius
R_e	Distance from source emission location to observer
Θ	Blade azimuth
St	Strouhal number
t	Observer time coordinate
T_{ij}	Lighthill's stress tensor
U	Fluid velocity
p_{ij}	Fluid stress tensor
r	Distance from source to observer
u_i	Unsteady component of the velocity

Abbreviations

AOA	Angle of Attack
VAWT	Vertical Axis Wind Turbine
TSR	Tip Speed Ratio
CSM	Cross Spectral Matrix
TBL-TE	Turbulent Boundary Layer - Trailing Edge
FFT	Fast Fourier Transform
HAWT	Horizontal Axis Wind Turbine
LBL-VS	Laminar Boundary Layer - Vortex Shedding
BVI	Blade Vortex Interaction
SPL	Sound Pressure Level
TEB-VS	Trailing Edge Bluntness - Vortex Shedding
TV-FORM	Tip Vortex formation

CHAPTER 1: INTRODUCTION

Due to global warming and greenhouse gas emissions, global orientation is moving towards the unstained sources. With growing issues concerning weather change and increment in pressure on the natural resources, it is time to search for greater sustainable power assets generated using renewable resources. One of the most auspicious renewable sources is wind energy. Globally wind energy is playing the most important part in the production of power using renewable resources [1].

1.1. Wind Energy

Wind energy can also be considered as a type of solar energy. The principle process of the wind turbines is to convert kinetic energy which is extracted from the wind into the mechanical power that is further used to run the generator. Some of the different circumstances due to which wind causes. Few of them are as follows:

- Atmosphere heating due to the sun.
- Variations on earth's surface.
- Earth's rotation.

The winds forms are likewise affected by different sources including mountains, water bodies, and vegetation.

1.2. Advantages of Wind Energy

There are multiples cons of wind energy as compared to conventional energy generation sources. Some of the cons are as follows [2]:

- Wind power is one of the most sustainable power source in now a days. It coasts almost 3 to 5 pennies per KW-h. As compared to the conventional power plants it does not rely on the fuel or gas. Other conventional power plants are expensive in running cost.
- Wind power brings about the arrangement of clean power accordingly fulfilling the worldwide climate concerns and satisfying the destinations of decrease of CO2 and other unsafe poisons delivered structure ordinary energy generators.
- Due to their size they utilize small amount of land so the farmers can raise these in their farms accordingly, which results the profit for both the land owner and economy.

- Water shortage is one of the significant issues in different pieces of the world. Wind energy has a little water utilization impression and will in general preserve water to help annihilate the water lack issues.

Nonetheless, noise generation might be viewed as a weakness of wind turbines. For this reason, overall examination is being led to lessen the noise signature and to make the wind turbines a more practical alternative of energy generation. For this reason, it is critical to comprehend the fundamental wonder behind wind generation.

1.3. History of Wind Turbines

Wind turbines since century were being utilized for granulating grains, siphoning water from ground and in present day for power age which are explicitly alluded to as wind turbine generators or WTG's the place as others with yield as mechanical energy are being named as wind mills.

Peripheral history of wind turbines begins with Heron of Alexandria from first Century A.D. who is known for designing first wind-controlled wheel.

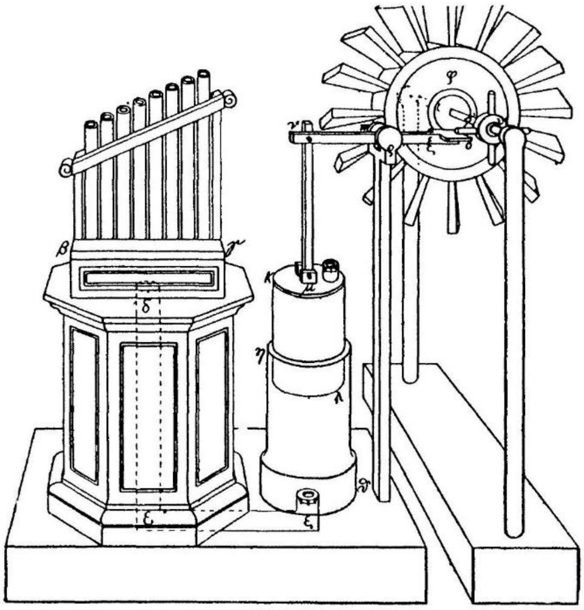

Figure 1: Heron's Wind Wheel

By 7th Century A.D. Persians were known to have wind turbines for pumping of water for agriculture in the region of Seitan and grinding of grains [3]. This is the first ever practical use of wind turbines. This turbine is known as PANEMONE windmill. It is the vertical axis wind turbine which uses the drag component. It is a vertical axis drag type wind turbine. It was made with sails made of fabric (four to Eight in numbers) mounted around an axel. As the wind blew it pushes the sails to create a circular motion and thus deriving the axel.

Figure 2: Panemone Windmill

By 10th century A.D. windmills were reportedly used in china to pump out salty sea water to make salt from it.

By 1180's drag type windmills were reportedly functional in northwestern Europe for grinding flour and for irrigation purpose.

These windmills started improving in design starting from rough ones to sophisticated ones. And with the passage of time horizontal windmills were introduced and become popular. By 12th Century A.D. Europeans built post windmills which became popular and then POST WINDMILL design usage peaked in 18th and 9th century and then suddenly declined after the invention of much faster and powerful steam driven machinery. Some of these Post windmills are still in working condition.

Figure 3: Quainton Windmill

Firstly, known wind turbine which is used to produce the electricity was made by Scotland Professor James Blyth [4] in 1887 from the Anderson's College. Turbine have sails cloth which was used to power the cottage for scientific purpose.

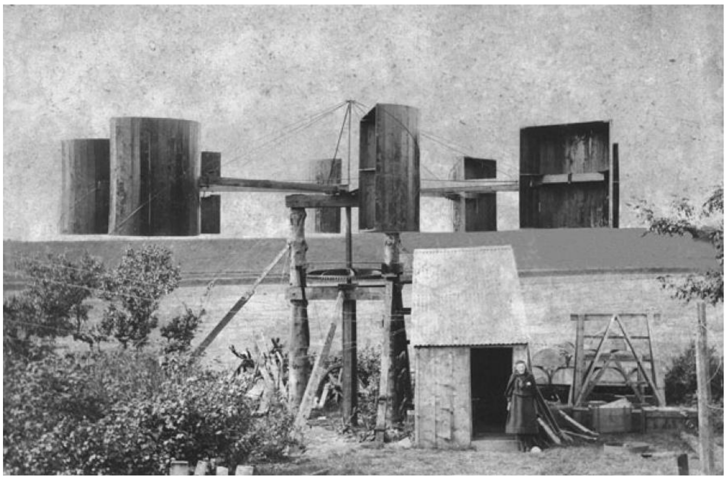

Figure 4: Prof. James VAWT

In 1888 first electricity producing wind turbine of America was developed by Charles Brush [5] in Ohio.

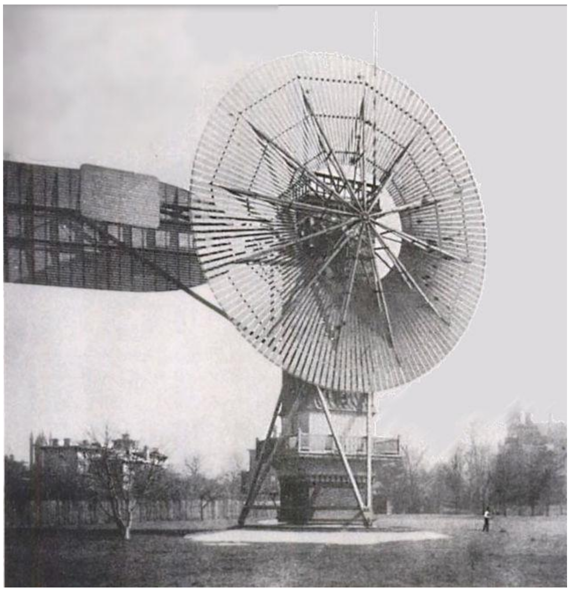

Figure 5: Brush Wind Turbine

The beginning of 20th century lead to many improvement in the field of wind turbine generators. Scientist name Pour La Cour find out a way to provide electricity via wind turbine generator and was able to provide electricity to the village and founded a Wind Electricians society in 1903. He was the first person who found out that wind turbine operates on higher rpms and less blades were more efficient wind turbines.

In 1931 Georges Jean Marie Darrieus [6] present a new type of turbine which is lift type vertical axis wind turbine called Darrieus VAWT.

In 1941 First wind turbine producing 1.25 Mega Watt of electricity joins the grid. It was called Smith-Putnam wind turbine, has 75 feet long blades, and was erected in Castletown, Vermont.

Small wind turbines were also used in WORLD WAR-II by Germans for charging submarine batteries using their U-Boats.

In 1957 Johannes Juul who was the student of La Cour, build a horizontal axis wind turbine which have 3 blades with diameter of 24m with power of 200 KW. He was the 1st to introduce aerodynamic tip brake. This turbine still in use now a days.

Business improvement in wind energy segment begins with the fuel emergency of 1970's that pushed the legislatures to search for elective methods of energy generation. By 1975 NASA lead program had the option to put online first windfarm of USA that had the ability to give capacity to over 4000 homes.

Leading offshore wind farm including 11 wind turbines every one of 450 Kilowatt was raised in Southern Denmark in the year 1991.

By fourth June 2019 the worldwide wind power limit came to 597 Gaga-Watt as indicated by world wind energy council.

1.4. Wind Power in Modern World

A recent announcement from World Wind Energy Association (WWEA) has revealed that as of 25th February 2019 globally capacity of wind turbines has reached 597 Gigawatt. China has largest market for wind energy with an installed capacity of around 200 Gigawatts. USA lags china having an installed capacity of around 100 Gigawatts. Since year 2017 an increment of 50.1 Gigawatts installed capacity of wind power is observed in the year 2018.

On small scale as of the end of 2015 small wind turbine installed capacity has reached 945 Mega-Watts. Out of about 990000 units installed worldwide China leads with 93% of the total installed capacity around the world. Small wind turbines units have advantage that they could be installed in hybrid energy units along with solar cells to provide sustainable energy solution to in a given location.

1.5. Types of Wind Turbines

Basically, there are two types of wind turbines that can be used for the extraction of power from wind energy. Both the turbines produce energy by directing the coming flow of air through the blades. These two types of turbines are as follows:

- Horizontal Axis Wind Turbine
- Vertical Axis Wind Turbine

1.5.1. Horizontal Axis Wind Turbine

Horizontal Axis Wind Turbines (HAWT) are the most executing wind turbine in all over the world. Some of them are the lift driven HAWT. There axis of rotation is aligned to the ground axis at any instance every blade is contributing to the lift force thus are more efficient than any other wind turbine. HAWT are usually categorized based upon number of blades or based on their orientation in the wind i.e. upwind and downwind.

The blades of the HAWT are set in such a way that the angle of attack is used to produce the lift force. One of the components of the lift force is in direction of the motion of blades thus resulting in the generation of torque. To maintain the AOA, blade velocity changes with the twist angle and radius of blade need steady variation throughout the blade span. More force is generated at tip due to the higher tip velocity. Furthermore, Marnoto ae al [7] observed that the angle of attack of blade is not the function of azimuth so generating maximum power the angle of twist between should be at optimum value.

Most of the HAWT have three blades attached to the central axis with the help of supporting structure called hub which allows pitching movement of the blades to increase or decrease generated lift force which helps both in starting the turbine rotor and stopping it in higher wind conditions. Few blades yield higher tip speed ratios, but higher number of blades yield lower tip speed ratios and smooth operation. Due to lower tip speed ratios associated with higher number of blades, three bladed turbines are quitter in operation than two or single blade turbine.

a b c

Figure 6: (a) Single Blade HAWT **(b)** Double Blade HAWT **(c)** Three Bladed HAWT

In order to maximize the performance of the turbine the Yaw mechanism is used along the blade pitching. There are two types of yaw mechanism whare are active and passive yaw mechanism [8]. They are usually adapted to face the turbine the wind direction. Their performance can severely affect by the wind direction. In HAWT there are further two types of turbines which are upwind HAWT and downwind HAWT as shown in figure 9.

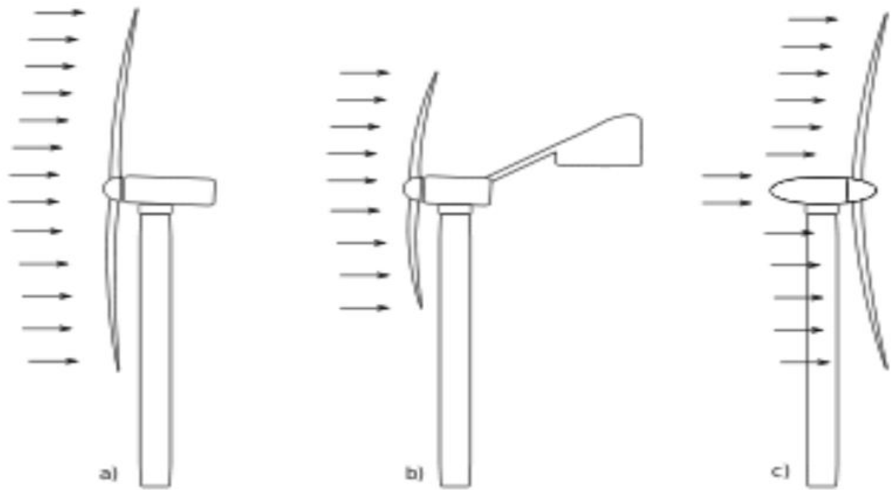

Figure 7: HAWT based on orientation in the wind (a) Upwind type with active yaw (b) Upwind type with passive yaw (c) Downwind type with passive yaw

In active yaw mechanism yaw is offered by electric motors or hydraulic system to direct turbine in the wind direction. While in passive yaw, yaw movement is controlled by tail rudder attached to the wind turbine and it acts with the force of the wind. Both systems are crucially important in high efficiency operation and safety of turbine. At higher wind speeds active yaw system faces away the wind turbine rotor from wind direction to protect turbine rotor whereas in passive yaw, Fluring acts to save wind turbine from damage in high wind speeds. In Fluring when the turbine's rotational inertia becomes significant the tail rudder partially disconnects itself from the turbine and due to rotational inertia turbine rotates on its vertical axis and faces away from wind direction.

1.5.2. Vertical Axis Wind Turbine

VAWT has blades introduced on head of a fundamental shaft rather than in the front as if there should in case of HAWT. The power generator for transformation of wind energy is generally introduced in the base of the pinnacle. Even though these sort of wind turbines are not a lot of normal, yet they offer more applied applications in the urban areas. There are two different types of VAWT which are categorized based on aerodynamic forces as drag or lift type.

1.5.2.1. Drag Type VAWT

Savonius VAWTs are drag type turbines. Although they follow that same principle of operation as that of previously known wind turbines, but this turbine's design was proposed by Finish Engineer Sigurd Johannes Savonius in 1922 and he patented it in 1929. He used curved airfoil for blades which convert the air velocity into driving force of turbine. Its rotor cross section looks like 'S shape'. One half of the cross section is contributing to the rotational force of the turbine. Its tip speed ratio at most could reach one times the velocity of free stream air [9]. These are less efficient wind turbines, but they have lower cut-in velocity which makes them a good choice for areas with lower wind speeds and for near ground operation. This turbine design is used in anemometers for wind speed measurements. They are also incorporated with lift type VAWT to assist them in rotation at lower air velocities.

Figure 8: Savonius Vertical Axis Wind Turbine

1.5.2.2. Lift Type VAWT

In lift type there are three basic geometries of wind turbine that exists today. Troposkien Darrieus (egg beater), straight blade or H-Rotor type and curved blade or Helical type VAWT. Lift type VAWT was patented in 1931 by George Jeans Marry Darrieus. Darrieus turbine has a central mast with two or three blades attached to it wind interacts with the blades which results in lift and drag forces. When the lift force becomes greater than drag force then the turbine starts rotating. It can achieve higher rpm as compare to drag type VAWT. Blades therefore plays crucial role in VAWT performance. At some instance only a fraction of blades is contributing to the lift force of turbine therefore these turbines have less efficiency as compared to horizontal axis wind turbines.

Troposkien is a Greek word meaning “rotating rope”. It has a curved blade which looks like a rope attached to central mast. Egg beater blades are difficult to manufacture and has low structural integrity. At low tip speed ratio egg beater blades has higher absolute angle of attack that causes blade to stall due to higher drag values. Therefore, its faces starting problems at low wind speeds [10]. Darrieus VAWT are mostly used in power generation due to its denseness and flexibility for residential installation [11, 12].

a b c

Figure 9: (a) H-Rotor VAWT (b) Helical VAWT (c) Egg Beater VAWT

Gorlov Helical turbine is derived from basic Darrieus turbine design. Its design was proposed and patented in 1995 by Professor Alexander Gorlov from Northeastern University Boston, Massachusetts. This design discourse the pulsating torque of previous models. At any given angle a fraction of turbine blade is present which reduces abrupt changes in distribution of lift and drag forces thus suppressing torque ripple, vibration and noise issues [13].

1.6. Small Scale Wind Turbines

International Electrotechnical Commission (IEC) was formed in 1906. Since then it is involved in the safety and design regulations of electricity consuming and electric energy producing devices. It also has a special section that deals with the safety and design regulation of wind turbines. IEC 61400-2 gives somewhat practical definition of small-scale wind turbines and refers any turbine with a swept area of less than or equal 200 square meter as small-scale wind turbine. It includes turbines with a rated power output of 50 kW. This definition is accepted all over the world except some countries who have their own standardizations to define small wind turbines (SWT).

In most cases turbines produce different effects such as where the turbines are large and small, they produce subjective and interference-effect. While in new turbines they only produce the subjective effect. If such a situation came where the work is inside any plant or beside aircraft, then the physiological effect is produced [14].

Other than the large capacities wind turbines which are in the MW range, small wind turbines having a small capacity (less than 10kw) are mostly used in the domestic areas for more usage of wind energy [15]. German Wind Energy Association (BWE) refers them as turbines with rated capacity of less than or equal to 100kW while residential systems should not have rated capacity of more than 30kW.

From university of Calgary Canada Professor David describe some features of Small wind turbines as

- Over speeding wind turbines is controlled by yaw devices and mechanical brakes.
- Small wind turbines are normally incorporated with direct drive permanent magnet generators (PMG) and rarely by doubly fed induction generators (DFIG).
- Small scale wind turbines aerodynamics is strongly influenced by low Reynold numbers. Their performance is closely related to their models tested in the laboratories.

1.7. Wind Turbine Rotor Characteristics

1.7.1. Basic Terminologies

- **Angle of Attack:** Incident angle between the air with the airfoil chord.
- **Chord:** It is the straight line which joins the leading edge with the trailing edge.
- **Leading Edge:** It is the front part of the airfoil which have maximum curved structure.

- **Trailing Edge:** It is the back end of the airfoil; it also has the maximum curvature. When the AOA is less the airflow start separated by this end of airfoil.
- **Camber:** The line which divides the airfoil into two equal parts.
- **Pressure Surface:** It is the lower part of the airfoil which relates to minimum velocity of air but high pressure.
- **Suction Surface:** It is the upper part of the airfoil which relates to maximum velocity of air but less pressure.
- **Maximum Thickness:** The maximum thickness of airfoil when measured perpendicular to the camber line.

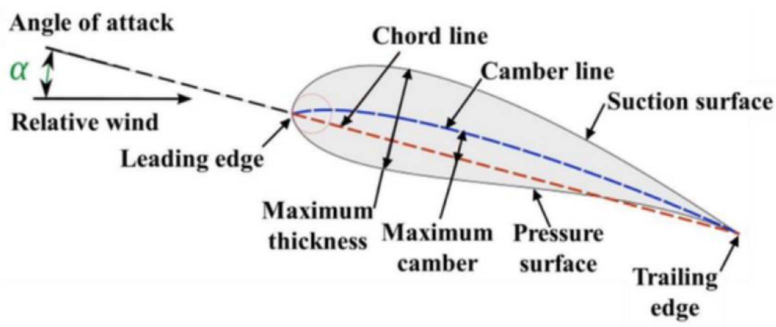

Figure 10: Labeled Airfoil

1.7.2. Basic Calculations

Globally winds are caused by pressure difference in the earth atmosphere due to un even heating of land around the globe. Winds generated by this cause are then captured by wind turbines to produce electricity.

It has long been established that a fluid in motion possesses energy and with the application of correct machinery, it can be used to extract useful work. Equation 1.1 helps to get an estimate of how much power can be generated from a particular wind source.

$$\textit{Kinetic Energy} = \frac{1}{2}mV^2 \tag{1.1}$$

$$\textit{Kinetic Energy}\; x\frac{1}{t} = \frac{1}{2}\frac{m}{t}V^2 \tag{1.2}$$

Where m/t is the mass flow rate of air particles and mass flow rate of air through a given area is given as

$$\frac{dm}{dt} = \rho AV \tag{1.3}$$

$$P = \frac{1}{2} AV^3 \tag{1.4}$$

P = Power possessed by air (measured in Watt)

V= velocity of air (measured in m/sec)

A = Area of cross section under consideration (measured in m^2)

ρ = Density of Air (measured in kg/m^3)

The equation 1.4 gives an estimate of the power of the fluid flowing through an area A. The equation also indicates that the energy is directly proportional to cube of velocity thus indicating that the amount of energy is highly dependent on the speed of wind. From this, it can be concluded that the installation of wind turbines in the windy areas is required to produce significant amounts of energy. Another important factor to consider is that the short duration, high speed gusts may contain the higher proportion of energy in gusty winds

1.7.2.1. Power Coefficient

Coefficient of performance defines wind turbine performance by the following formula

$$P_{air} = \frac{1}{2} C_p \, \rho A V^3 \tag{1.5}$$

where

C_p = Coefficient of performance of turbine restricted by Betz Limit

BETZ Limit was proposed by German Physicist Albert Betz in 1919. According to him theoretically wind turbine can only extract about 59.3%.

1.7.2.2. Rotor Solidity

Rotor solidity is basically the measure of blockage to the wind offered by wind turbine blades. It is mathematically represented as under

Here

$$\text{Rotor Solidity} = \sigma = \frac{N\,c}{2R} \tag{1.6}$$

N = Number of Blades

R = Radius of VAWT

c = chord of blade profile

Higher value of rotor solidity will reduce turbine rpm while its torque will increase.

1.7.2.3. Tip Speed Ratio

TSR is defined as the ratio of maximum blade velocity to reference air velocity

$$\mathbf{TSR} = \lambda = \frac{\omega R}{V} \tag{1.7}$$

Where ω = angular velocity of turbine

1.8. Noise

One of the major drawback or and implication of using the wind turbine is the noise annoyance. The noise is categorized into different types. The four general types are indicated as follows:

1.8.1. Continuous noise

It is a type of noise that is produced continuously without interruption. An example can be considered of machinery that runs without any interruption.

1.8.2. Intermittent Noise

This is a type of pulsating noise that decreases and increases rapidly. An example can be considered of a train passing by.

1.8.3. Impulsive Noise

This corresponds to the sudden bursts of noise that may startle you because of their surprising nature. These are usually created by construction equipment, explosions etc.

1.8.4. Low Frequency Noise

A constant noise with low frequency that is a part of our daily soundscape fabric. This noise usually does not have a disturbing nature yet long-term exposure can affect the hearing of a person. An example is the background hum of a power station. These noises require the highest consideration as they tend to affect people more without them knowing as compared to other types.

These were some of the characteristic noises that are encountered on daily basis. Each one has its own implications and all of them damage the hearing capabilities and may ultimately lead to hearing loss.

In case of wind turbines mounted close to residential areas, the residents may experience the continuous sound of the blades, intermittent noise caused by the striking of wind gusts with the blades and the low frequency noise of the power generating equipment. Out of these, the mechanical hum of the generator and the continuous noise play an active role in disturbing the environment. The swishing sound of air can have frequency between 63 Hz to 4000 Hz.

This sound level decreases as the distance from the wind turbine increases. The wind and the weather conditions also affect the means of sound propagation. Even the soil type and the water can have damping effect for the sound [16].

1.9. Advantages of VAWT over HAWT

HAWT have higher aerodynamic efficiency than VAWT as in HAWT as all blades are contributing to the lift and therefore because of this reason HAWT is mostly preferred and well adapted turbine around the globe. Apart from this there are certain disadvantages of HAWT that makes the VAWT a preferred wind turbine generator[17]. F. Trivellatoa, and M. Raciti Castelli describes the advantages of VAWT as under.

- In HAWT the turbine yaw mechanism is must for facing turbine in the wind direction which is costly and thus increasing per unit cost of the turbine. VAWT however is omnidirectional in nature thus do not require any such devices [13].

- HAWT perform better at higher wind speeds which are available at a certain height from ground therefore long towers are made for them and larger diameter of the blades. this overall structure has negatively perceived visual impact. Whereas VAWT on the other hand due to smaller diameter as compared to HAWT and ability to perform at lower heights thus creating a positive visual impact. Because of this reasons HAWT's installations are usually opposed by the residents.
- Due to simple design and structure of VAWT it has far less installation cost as compared to HAWT which is normally place in higher winds so heighted and stronger tower is needed for HAWT

- Generator of VAWT is commonly placed close to the round whereas in HAWT it is placed on top of the tower in casing called nacelle. Due to its placement it is difficult and costly to carry out maintenance operations for HAWT.

CHAPTER 2: Literature Review

Prior in the field of aeroacoustics, the fundamental spotlight was on the portrayal of frequency components in a sound field. Yet, the work on the assurance of force of sound field was embraced first time by Lighthill in 1952 [18].

2.1. Lighthill's Acoustics Model

Lighthill redeveloped the Navier-Stokes condition as a wave condition with an unmistakable source term on right hand side of the uniformity. This model is likewise alluded to as the "Lighthill's similarity" since it gives a mode for sound field that did not depend on material science of stream created noise yet it depends on the relationship of how they may be spoken to through the administering conditions of a compressible fluid. His work fills in as the establishment of hypothetical aeroacoustics. The model is demonstrated in the accompanying equation.

$$\frac{\partial^2 \rho}{\partial t^2} - a_0^2 \frac{\partial^2 \rho}{\partial {x_i}^2} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{2.1}$$

where $T_{ij} = \rho u_i u_j + p_{ij} - a_0^2(\rho - \rho_0)\delta_{ij}$ shows Lighthill stress tensor

Three different mechanism was described by Lighthill from which the Kinetic Energy was converted into the Acoustic Energy. Which are

- By driving a mass to oscillate in a fixed space. (Middle of an amplifier installed in a huge baffle)
- Generating fluctuations in momentum in a particular region in space or by varying the mass flux rate across fixed surfaces. (Example can be taken by a solid object vibrating after getting stuck)
- By changing the rate of momentum flux over fixed surfaces. (Aerodynamically generated sound with no fixed boundaries)

The lighthill equation deals only with the third mechanism. It cannot involve the fixed boundaries. As strong limits transmit sound all the more proficiently, so another condition that additionally obliges their effect must be applied while considering the sound produced by a strong moving body [19].

2.2. Ffowcs Willimas-Hawkings Equation

In 1969 William's and Hawking's [20] developed a formulation for modeling the sound produced by surfaces in random (arbitrary) motion. A general function f was defined such that $f = 0$ on body surface and utilizing the equations of conservation of fluid mechanics, the following relation was developed:

$$\frac{\partial^2 H(f)\rho}{\partial t^2} - a_0^2 \frac{\partial^2 H(f)\rho}{\partial x_i^2} = \frac{\partial^2}{\partial x_i \partial x_j}\left[H(f)T_{ij}\right] - \frac{\partial}{\partial x_i}\left(p_{ij}\delta(f)\frac{\partial f}{\partial x_j}\right) + \frac{\partial}{\partial t}\left(\rho_0 v_i \delta(f)\frac{\partial f}{\partial x_i}\right) \quad \textbf{(2.2)}$$

The above equation is commonly used in aero-acoustic theory. Each source term depicts one of the noise generation mechanism as described by Lighthill. Their description is as follows:

- $\frac{\partial^2}{\partial x_i \partial x_j}\left[H(f)T_{ij}\right]$ - This is due to momentum flux across fixed surface not involving solid boundaries. The double space differential indicates that it is a quadrupole source.
- $\frac{\partial}{\partial x_i}\left(p_{ij}\delta(f)\frac{\partial f}{\partial x_j}\right)$ – This is because of fluctuating forces and is usually referred to as loading noise. The single space differential indicates that it is a dipole.
- $\frac{\partial}{\partial t}\left(\rho_0 v_i \delta(f)\frac{\partial f}{\partial x_i}\right)$ – This is because of displacement of fluid volume and is referred to as thickness noise. It is monopole source.

However, care must be taken while discussing the dipole and monopole sources as their definition for the moving surface may be misleading.

2.3. Equation of Acoustics Wave

For the solution of wave equations, often the generalized functions are employed. In order to solve these equations, the general approach is to breakdown the source in multiple discrete point sources. For solving the FW-H equation, the generalized function employed is Green's function of wave equation in three-dimensional unbounded space. A quality clarification about the solution of acoustics waves was found in 1964 by Jones [21]. In order to solve the acoustics equation, the equation should break into number of discrete sources. That form can used to solve the FW-H equation. The following equation shows the flow for zero mean.

$$G(x_i, t; y_t, \tau) = \frac{\delta\left(\tau - t + \frac{r}{a_0}\right)}{4\pi r} \quad \textbf{(2.3)}$$

Where,

$$\boldsymbol{r} = \boldsymbol{x_i} - \boldsymbol{y_i}$$

To grasp the concept of the above relation, consider the condition,

$$\boldsymbol{g} = \boldsymbol{\tau} - \boldsymbol{t} + \frac{\boldsymbol{r}}{\boldsymbol{a_0}} = \boldsymbol{0}$$

This equation can be rewritten as,

$$\boldsymbol{a_0}(\boldsymbol{t} - \boldsymbol{\tau}) = |\boldsymbol{x} - \boldsymbol{y}|$$

The surface can be considered as a sphere having the center at observe location x_i. Now, there is a decrease in the sphere radius from infinity to zero with the increasing source time from $\tau = -\infty$ to $\tau = -t$ alongwith the contraction rate equal to speed of sound, a_0. This decreasing sphere indicates the locus of all the possible acoustic sources that may create a sound that will arrive at observer at time t [22].

In addition to the above-mentioned correlation, the most commonly used solutions to FW-H equations are the formulations of Succi [23] indicated as 1 and 1A

All these formulations are used to get the theoretical results. However, these results can only be complemented by an experimental analysis and without it, these results would be of little benefit.

2.4. Noise Prediction Methods

There are also some disadvantages of the wind energy that are causing not to becoming the wind turbines popular, one of the major problems is the acoustic pollution in the residential areas. Acoustic noise causes the disturbances between the neighborhoods, especially which are having low ambiance noise zone [24]. The frequency-domain of wind turbines sounds are mainly at low values which are sometimes muffled to higher values in the normal listening range [25]. The human normal hearing range is from 20Hz to 20kHz while the 3 to 4 kHz region is the most sensitive region for the human ear. The human ear follows harmony or noise as a separate response to the sound amplitude [26].

Noise transmitted from a working wind turbine can be classified into two categories: mechanical noise and aerodynamic noise. Mechanical noise generates due to the mechanical components in the turbine such as the gearbox, generator, and shaft. Machinery noise can be decreased precisely with the help of many engineering methods [27]. Aerodynamic noise is generated due to the blades and the association of the turbulence with blades. Therefore, it is the most important parameter to identify and anticipate the important noise source. This aerodynamic noise is divided into two categories; tonal noise and broadband noise [28]. The first tonal noise contains discrete harmonics (at a single frequency) or broadband noise that comprise random, nonperiodic signals caused by turbulent flow over the blades. These nonperiodic signals are generally greater than 100 Hz. Mainly the low-frequency tonal noise occurs at the blade passing frequency (no of blades into rotation speed of the wheel) [29]. Pederson et al.[30] concluded in his work that the swishing noise was the most disturbing noise to hear and then replaced by blared and tremble noise. It was also studied that people start feeling irritated when the level of noise is increased. The noise coming from the turbine is relatable to irritating noise from random traffic [31].

Using the computational methods to predict the sound generation offers a challenging problem. In case of vertical axis wind turbine, it is imperative to model global flow passing through the entire rotor and resolving blade flow at the same time with accuracy that is high enough for prediction of unsteady pressure loadings. This would also require high temporal resolution. Because of these difficulties, the computational methods are rather more expensive as compared to the empirical ones. This led to the development of various empirical and semi-empirical methods for the prediction of acoustic sources

2.4.1. Trailing Edge Noise

As trailing edge experiences, the turbulent flow that passes over an aero foil, it results in the production of noise due to the scattering of pressure fluctuations. This noise is referred to as the broadband noise which is considered as one of the most dominant sources of aero-acoustic noise. This type of noise can be modeled using the FW-H formulation in a particular time domain. However, higher accuracy predictions usually require high resolution aero-dynamic inputs. Different frequency domain methods were developed in order to model this type of noise.

FW-H [32] were the first to carry out the initial analysis of sound scattered by a sharp edge. It utilized the Green's function with zero mean flow. The main findings of this work included:

1) The scattered noise from trailing edge is scaled as the 5th power of Mach number of blade.
2) The angle that the trailing edge makes with means flow is related to Acoustic intensity.

Another important model and the most commonly used, was developed by Amiet et al [33]. It modeled the far-field PSD that is propagated by a known turbulent flow moving past a sharp edge. According to this model, it was assumed that turbulence is frozen meaning that it is simply convicted at mean velocity over the trailing edge. The main input of the model is the spectrum of turbulent pressure fluctuation in flow. The findings are listed below:

- The sound generated but the self-induced boundary layer turbulence is much quieter as compared to an inflow having 1 % turbulence intensity unless the airfoil stalls.
- The air flow around the blade is likely to stall at some points, thus making it possible that the scattered turbulent pressure fluctuations could contribute to the production of sound.

One of the assumptions of this model is that the flow is assumed to be steady. Thus, application of this model requires a lot of care.

2.4.2. Tonal Noise of Laminar Boundary Layer

Previously, the flow over the trailing edge was assumed to be turbulent. In this case, it is indicated that at the trailing edge, if the flow over the pressure surface is laminar, it would result in the production of tonal noise. According to Tollmein et al [34] , this particular noise was produced as a result of feedback mechanism. Furthermore, the Tollmein Schlichting waves frequency is influenced by acoustic waves coming from the wake of blade reinforcing certain components of frequency in flow.

In order to predict the frequency of tonal components, the empirical relations were developed by Tollmein et al. [34] and Vogt et al. [35]. The equations used are as follows:

$$f_{n,max} = \frac{KU_{\infty}^{1.5}}{\sqrt{cv}} \quad \textbf{(2.4)}$$

$$f_{n,max} = \frac{KU_{\infty}^{1.5}}{\sqrt{cv}} \quad \textbf{(2.5)}$$

Further development to this relation was done by Arbey and Bataille [36] making a modification to the exponent of tonal separation i.e. 0.85 thus resulting in better correlation with exp. data. They explained that the acoustic source in feedback mechanism was not the point in blade wake, but it was the trailing edge of blade.

Currently, the simulations have been carried out based on Arbey and Bataille [36] correlation for solving the flow model. These suggested that the exponent in separation equation should be 0.80 as it was proposed initially.

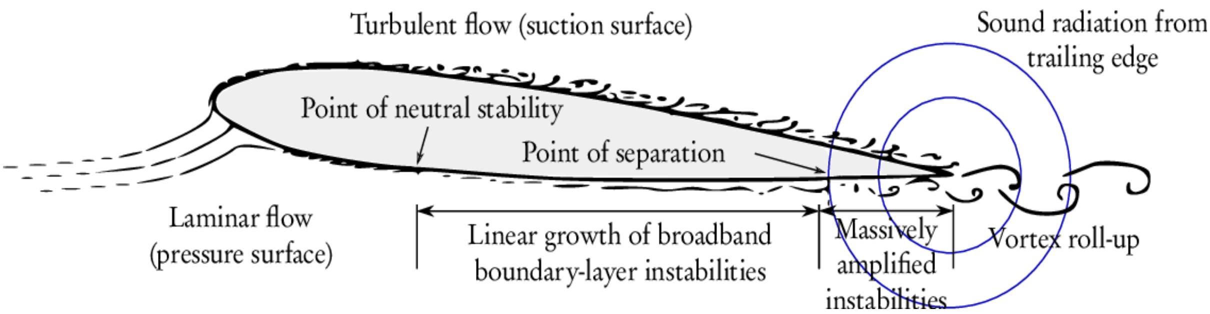

Figure 11: Tonal Noise Mechanism (Schematic Diagram)

2.4.3. Airfoil Self Noise

The aerodynamic noises are formed due to the various flow phenomena happening at the airfoil surface. Some reasons of self-noise studied by scientists at subsonic flow are as follows [37]:

a) Turbulent boundary layer trailing edge noise (TBL-TE).
b) Separation/stall noise.
c) Tip vortex formation noise (TV).
d) Trailing edge bluntness vortex shedding noise (TEB-VS).
e) Laminar boundary layer vortex shedding noise (LBL-VS).

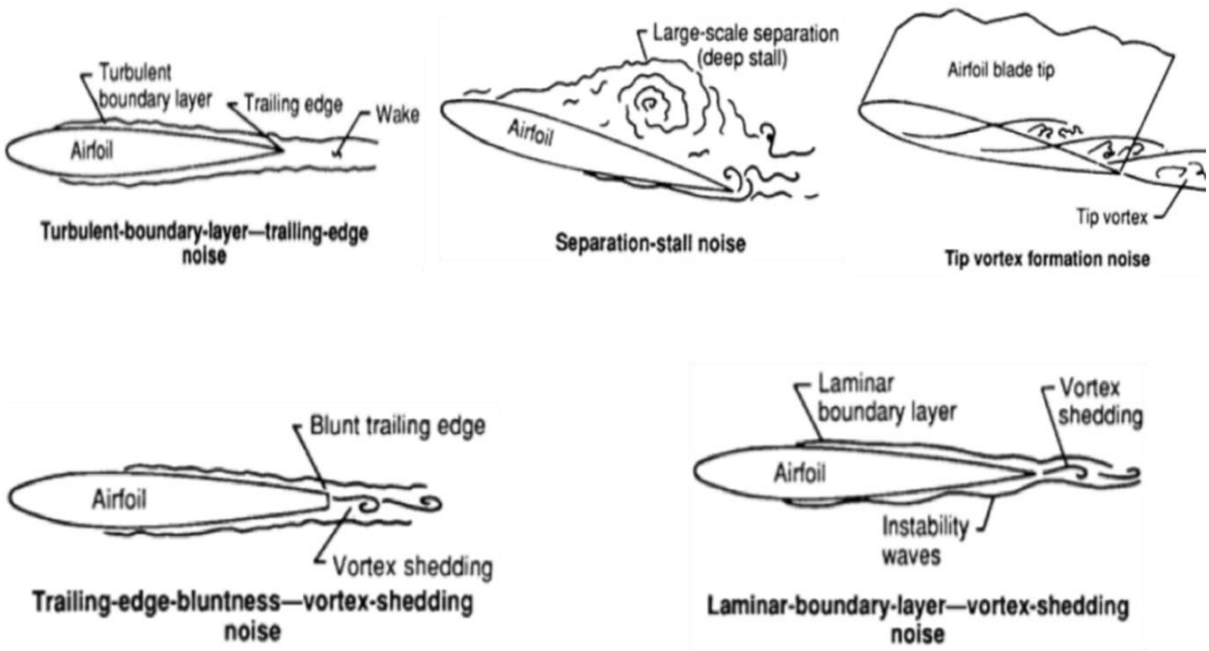

Figure 12: Self-noises sources schematic

2.4.4. Helicopter Noise

VAWT rotors have very similar aerodynamic characteristics with helicopters. In case of helicopters operating in sideslip mode, unsteady blade loads are generated because of the wake interaction from blade passages. This unsteady loading does not resemble in any way with HAWT but have a lot in common with VAWT.

This loading offers a strong noise source and can be analyzed using the Lowson model of unsteady point force [38] . According to this model, the noise is proportional to change rate of force. Studies have found that the rotor of helicopter generates high impulsive noise. There are two major sources of this impulsive noise. These are described in the proceedings.

High Speed Impulsive Noise

High speed impulsive noise occurs because of the occurrence of compressibility effects at tips of blades and is influenced by high Mach numbers. The VAWT are usually operated at lower Mach numbers therefore, this effect is negligible in this case.

Blade Vortex Interaction (BVI) Noise:

During rotation of VAWT, the blades shed vorticity due to fluctuation of circulation on the blades. At lower speeds, the blades may undergo dynamic stall thus shedding stronger vortices. The interaction between the downstream blade and vortex shed by the upstream blade results in the generation of noise referred to as the blade vortex interaction noise. The BVI generated by rotors of helicopters was found to be dependent on the following parameters:

- Tip vortex core size
- Tip vortex local strength
- Local angle of interaction between vortex line and the blade
- Vertical separation between the blade and the vortex

To decrease the noise signature, one of the four factors need to be catered. Usually, the shape of the blade tip is changed thus reducing either the strength of tip vortex, making it more diffused or both. However, the major concern is to reduce it without affecting the blade performance.

2.4.5. Inflow Turbulence

The loadings produced on an airfoil are highly dependent on the flow conditions. If the airfoil experiences an incoming turbulent flow, it results in the production of noise. It is a challenging job to characterize the wind turbulence accurately. [39] has worked on the characterization of large scale atmospheric turbulence. However, for small scale inflow turbulence, very little work is published. This is due to the fact most of the energy in wind is present in gusts which are the larger structure thus making small scales irrelevant. Furthermore, the small scales also tend to be site-specific.

Amiet et al. [33] derived a scaling relationship for noise generated as a result of inflow turbulence. It was further adapted and modified for use in various studies. All the studies noted that the noise generated as a result of inflow turbulence is very much sensitive to length scale of turbulence in scaling relationship. Gleg [1986] found that the best fit for the inflow model and measured data occurred when the turbulence scale was taken equal to blade chord.

Producers improved the expertise, having the option to present continually innovation in the journey for proficiency improvement and power large scale manufacturing. Wind farms are commonly installed on a precise study of the resources of the winding course in the specified area, but their design always causes restrictions due to the environmental side. It is simple to install wind turbines in remote areas but mostly is installed near the developed areas. All things considered, turbine noise exists, and their impacts can be significantly relying upon separation along with residence and wind turbines, yet in addition, relying upon wind course. Turbine noise is not as much as an airplane flying over the vicinities of an air terminal, yet the source is steady and tedious, emanating noise in an immense scope of frequencies. Such joined highlights make the turbine noise one of the major irritating noise hotspots for the individuals who are uncovered [40].

2.5. Moving Body Acoustics

Lighthill investigated the sound generated by a moving body through modeling the acoustic field of a point source in uniform rectilinear motion. The resulting equation is indicated as follows:

$$\boldsymbol{\rho - \rho_0 = \left[\frac{x_i - y_i}{4\pi a_0^2 r^2 (1 - M_r)^2} \frac{\partial F_i}{\partial t}\right]_{ret}} \tag{2.6}$$

Here,

$$F_i = Fluctuating\ Point\ Force$$

$$x = source\ location$$

$$y = observer\ location$$

$$M_r = Mach\ number\ in\ observer\ direction$$

The square brackets indicate that the equation must be evaluated at retarded source time. The square brackets are used in this form in the aero-acoustic field and this notation will be used onwards.

This work was further extended by Lowson et al. [38] allowing it for general motion thus introducing a new term in the relation because of the source acceleration. This result is beneficial for the preliminary investigations of acoustic field of a moving source as it tends to maintain most features of acoustic field and avoiding unnecessary complexity at the same time. This equation is only applicable for low subsonic speeds. The following equation serves as the basic of aero-acoustic model.

$$\rho - \rho_0 = \left[\frac{x_i - y_i}{4\pi a_0^2 r^2 (1-M_r)^2}\left\{\frac{\partial F_i}{\partial t} - \frac{F_i}{1-M_r}\frac{\partial M_r}{\partial t}\right\}\right]_{ret} \quad (2.7)$$

The above equation includes only farfield terms. The farfield terms are those that decay as 1/r rather than $1/r^2$. To find out when the far-field terms play a dominant role, it is imperative to understand the near-field terms. According to Lowson, the near-field component was described as:

$$\rho - \rho_0 = \left[\frac{x_i - y_i}{4\pi a_0^2 r^2 (1-M_r)^2}\left\{\frac{F_i(x_i - y_i)}{r}\frac{(1-M^2)}{(1-M_r)} - F_i M_r\right\}\right]_{ret} \quad (2.8)$$

In general, the acoustic field is the sum of far and near-field components.

2.6. Numerical Acoustics Analysis

In 2014 M.H. Mohammed [41] performed numerical analysis of VAWT using FW-H equations Solutions was done using URANS (unsteady Reynolds-averaged Navier-Strokes) equation. He studied numerically on the blade shapes, tip speed ratio and solidity effect of VAWT in his study. He installed number of mics on different location from the source as show in figure 13

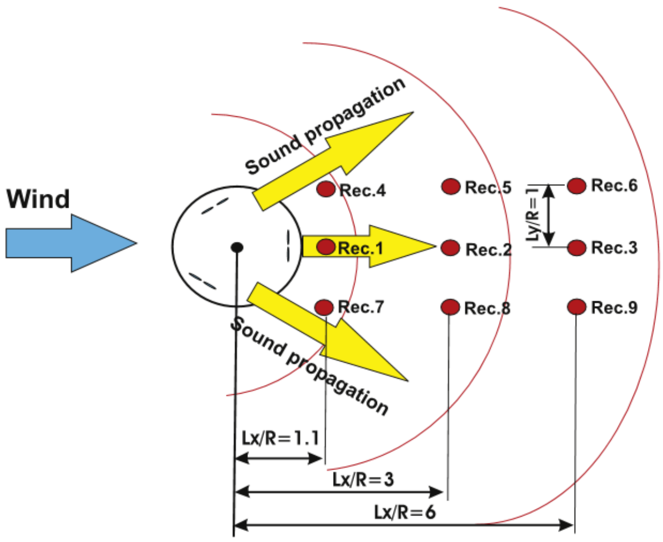

Figure 13: Sound wave propagation and microphone arrangement

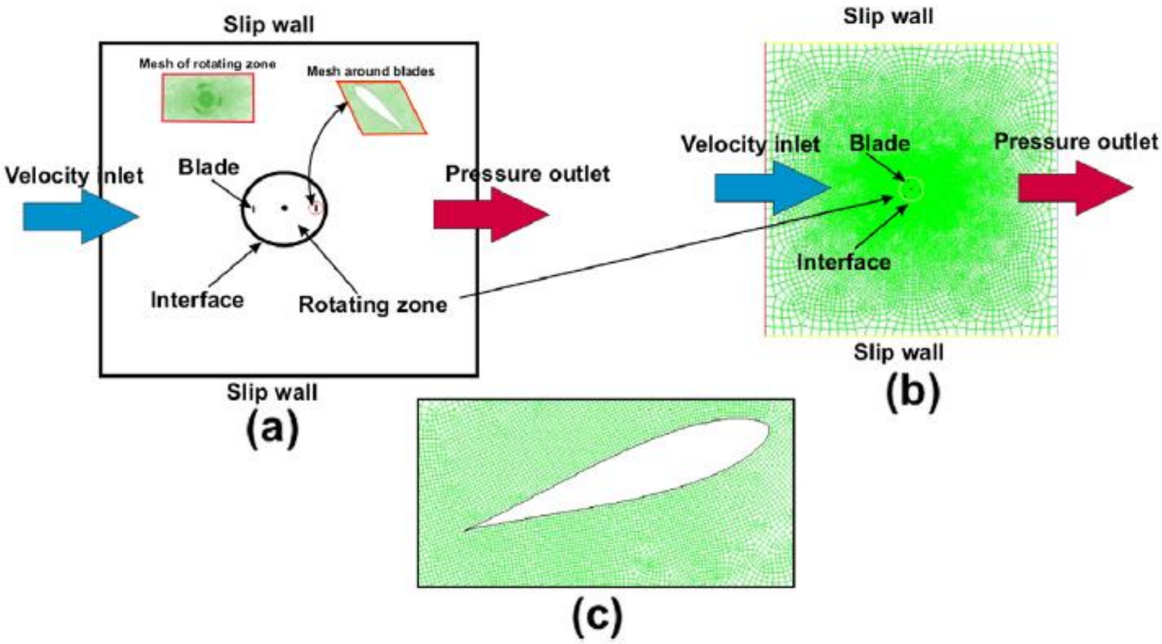

Figure 14: CFD domain and Meshing

M.H. Mohammed concluded that by increasing the distance between the source and the receiver the noise decreases, but the frequency of the noise remains the same. He also concluded that by increasing the TSR and solidity of the rotor the noise increases.

Monoplane VAWT are most common type of lift type VAWT available and is a reference case here. Alexandru Cismilianu and Alexandru Boros studied the performance of biplane VAWT about monoplane VAWT by operating them between at TSR of 2 to 2.5. Both turbines have same rotor solidity of 0.48%. it was observed that the Cl/Cd of biplane is more than that of monoplane VAWT given same geometric and atmospheric conditions. They also suggested that if the turbines are place at optimum distance from the buildings in urban environment where the wind potential is amplified by the edges and corners of the buildings then the performance of VAWT can be enhanced. According to them wind follows easiest path and corners and edges of the buildings increase the wind speed by 2 to 3 times and this can be capitalized by placing turbines as optimum distance from buildings where air have amplified effect [42].

Figure 15: Biplane Vertical Axis Wind Turbine

M.H. Muhammad performed 2D analysis to investigate the aeroacoustics characteristics of a new type of turbine with blades in Tandem orientation. Airfoil used for the turbine is S1046 and solidity of turbine is 0.1. These tandem blades were tested in 4 orientation with 0%, 20%, 60% and 90% blade spacing with respect to chord length. TSR of turbine is also varied and analysis were performed with TSR 3, 5 and 7. Nine microphones array is utilized to investigate the aeroacoustics effect of the turbine. Higher TSR results in higher noise levels and therefore it was observed the if TSR is varied from 7 to 3, average noise level ruction of 15.8 is observed. 60% blade spacing was observed as optimum spacing of blades in terms of both noise reduction and performance characteristics. Using 60% spacing average sound level reduction of 56.55% is achieved while only sacrificing 6.8% of torque and performance coefficient. This turbine is a unique design in terms of noise reduction studies [43].

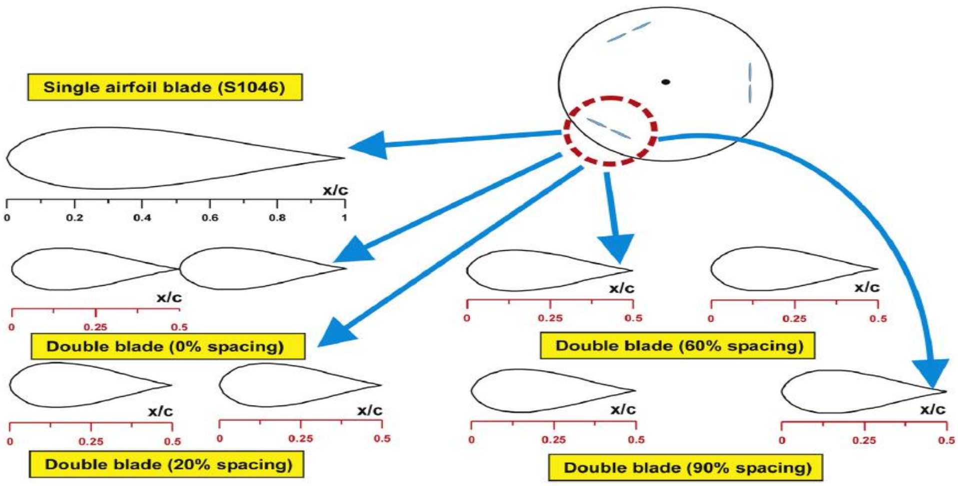

Figure 16: Configurations of Tandem VAWT

Ghasemian et al. [44] performed the series of LES (large eddy simulations) on five different TSRs (tip speed ratio) to investigate OASPL (overall sound pressure level). They concluded that there is a direct relation between the noise generation and the TSR. By increases the TSR the noise increases they also study the outcome of the distance of the receiver to the source.

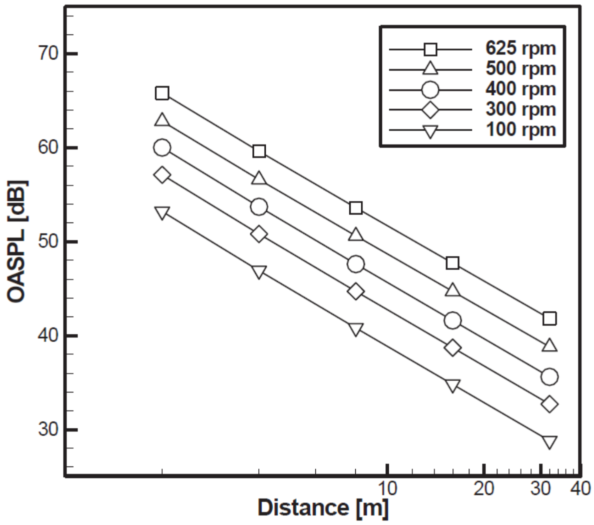

Figure 17: Distance vs OASPL (Ghasemian et al)

Chapter 3: Experimental Setup

The whole experiment is performed in the non-resonant chamber at the National University of Sciences and Technology, Islamabad acoustics lab. The actual setup of our experiment is shown in figure 18. The purpose of using a non-resonant chamber is to take the measurements that there will be no reflection of noise when it strikes with the wall and they only focused on the source. The absorption coefficient of our chamber is 0.6 at low frequencies. For the experimental purpose, the NACA-0012 airfoil profile is used for manufacturing three-blade of VAWT. NACA-0012 can be performed well at a specific Reynolds number, also, the dynamic stall of the blade is less when it reaches the maximum value of power coefficient as compared to other profiles. For the given VAWT the maximum reachable rpm is 300 rev/min. The specifications of our rotor are illustrated in Table 1. And the schematics of our array and blades are shown in figure 19**.** A setup for acoustic measurements involves a linear array of 8 (max 4466) microphones. The linear array is preferred because of its linear frequency response and self-cancellation capability of surrounding noise, furthermore, it can only capture the noise which is coming from its front [45]. For acquiring FFT data from the sensor, data acquisition is made by interfacing the NI-DAQ 6009 device with LabVIEW 2017 software. The distance between each mic was 200mm and the height of the microphones was approximately equal to the mid rotor height. This array has a range of 8 Hz to 20 kHz frequency spectrums.

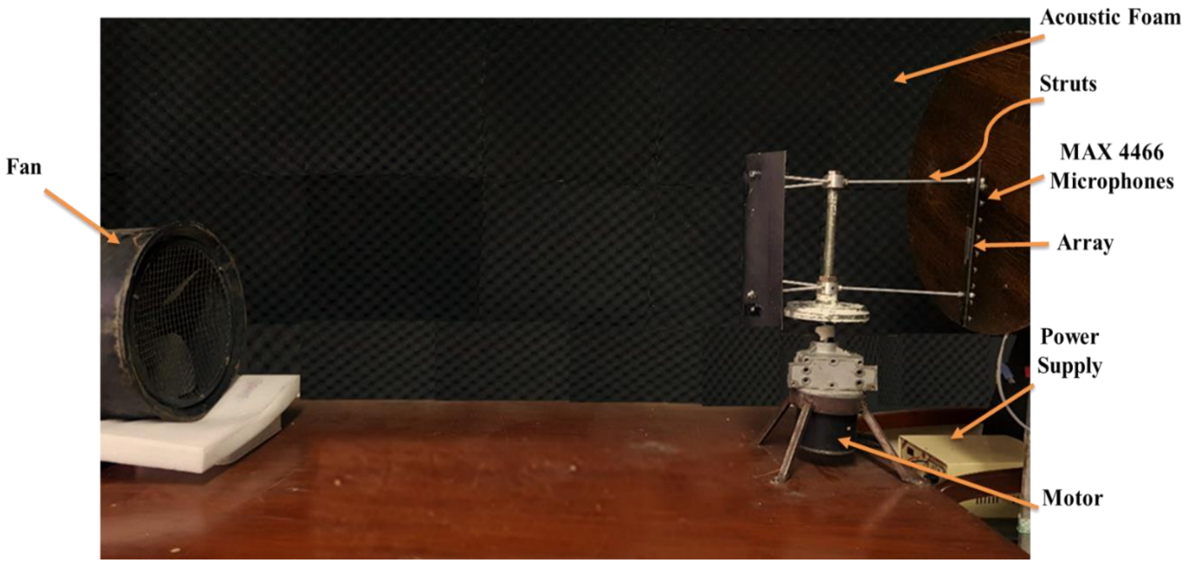

Figure 18: Actual Experimental Setup

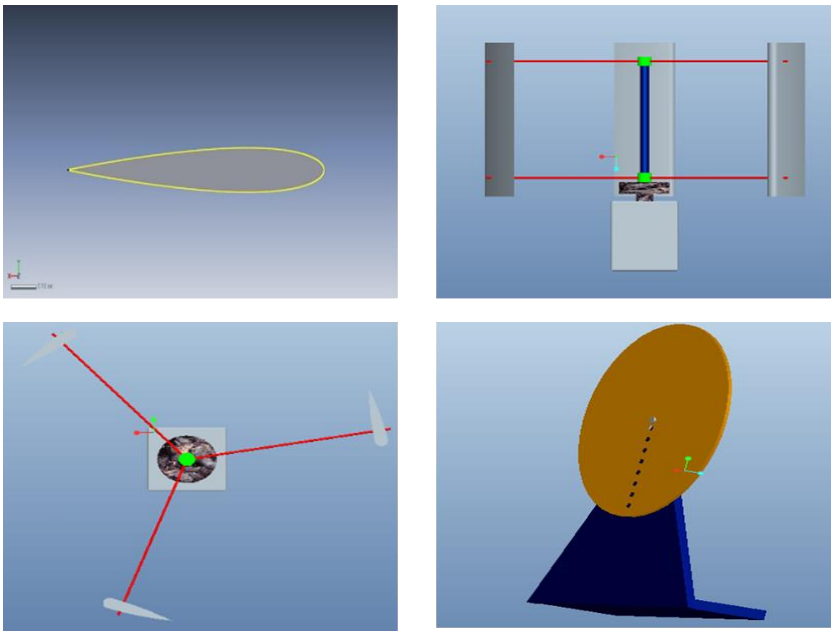

Figure 19: Schematic Diagrams of Setup

Table 1: Setup Parameters

Blade Profile	NACA-0012
Radius (mm)	300
Height (mm)	330
Chord Length (mm)	100
No of Blades	3
Blade Material	PLA
Shell Material	Stainless steel
Rated RPM	300

Table 2: Rotor Specifications

Sr. No	**Turbine rpm (rev/min)**	**Wind speed (m/s) (approx.)**	**TSR**
1	128	3.3	1.2
2	162	3.18	1.6
3	182	2.85	2
4	228	3.1	2.3

For executing study at different TSRs, the RPMs of the turbine were varied by changing the speed of the dc motor mounted to the turbine and by changing the wind speed which is maintained using fan speed. The turbine speed is varied by changing the voltages from the dc supply. The setup parameters of our experiment are shown in table 1. A digital laser tachometer is used to measure the rpm of the turbine. 6000 raw samples per second were obtained from the microphones. Then the algorithm obtains the RMS value of SPL and performed FFT on it which converts the signals into the dBs. For error reduction, averaging of 20ffts was performed on the single mic samples. To separate the tonal and broadband characteristics in the results, the high-resolution measurements are required. By analyzing the number of channels and setup measurements, 100 averages were extracted from which the immaterial noise cannot be separated but the peaks of maxima and minima can be clearly seen.

Chapter 4: Results and Discussion

The results accumulated from the microphonic array are compared with work done by Masoud et al. [44] and Weber et al. [46] and results are significantly relatable. They used NACA-0018 and NACA 4518, 3 bladed VAWT at 0.4 to 2.3 TSR which is compared with the same TSRs of our experiment, and after comparing both the graphs show the same trend as our graph.

Different experiments were performed on three different types of arrangements for the SPL calculation of VAWT. For every arrangement, four different TSR experiments were performed. For The first arrangement is the Monoplane VAWT in which there are 3 blades.

4.1. Error Reduction

For each microphones having 3000 samples, 20 FFT signals were obtained. By doing average of all the 20 FFT signals one value is obtained. It will reduce the error in our results.

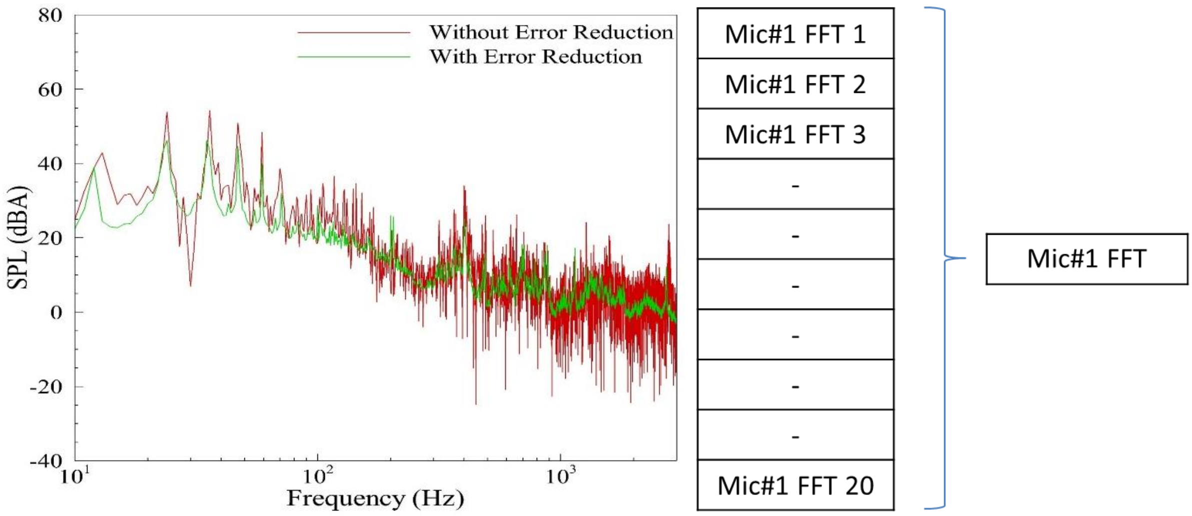

Figure 20: Error Reduction SPL (Averaging)

4.2. Monoplane VAWT

The accessibility of turbine blades changes the achievement of the H-Darrieus Turbine due to the interference of aerodynamic losses [47]. The H-Darrieus wind turbine performance depends upon the blade's interaction due to aerodynamics. That aerodynamics is due to the production of wakes by the blades. That reciprocity is due to the solidity effect of blades and the Tip Speed Ratio.

4.2.1. Solidity Effect

In this experiment, two types of solidity were taken in the study which was 0.5 and 0.75. From figure 21 the schematic diagrams of both solidities can be seen. The solidity ($\sigma =$ nc/2R) was changed by changing the turbine radius from 0.3m to 0.15m. Due to the effect of wake on blades, the attack angle increases which causes the blades to stall dynamically earlier, and the blades aerodynamic efficiency is also affected which lead to the generation of eddies, and more noise is produced [41]. The increase in solidity causes a decrease in the rotor radius due to which blades came nearer to each other, thus, when fluid flow over the blades it causes the wake production and due to which eddies are generated. When eddies of the first blade reach the other blade there will be very less amount of shedding due to which more sound is produced as compared to when there is less solidity (0.3m radius). SPL of two different solidities studied performed is shown in figure 22a and figure 22b representing that when the solidity increases the SPL is also increases. From solidity 0.5 to 0.75 there is an increment of sound by 7.99dB.

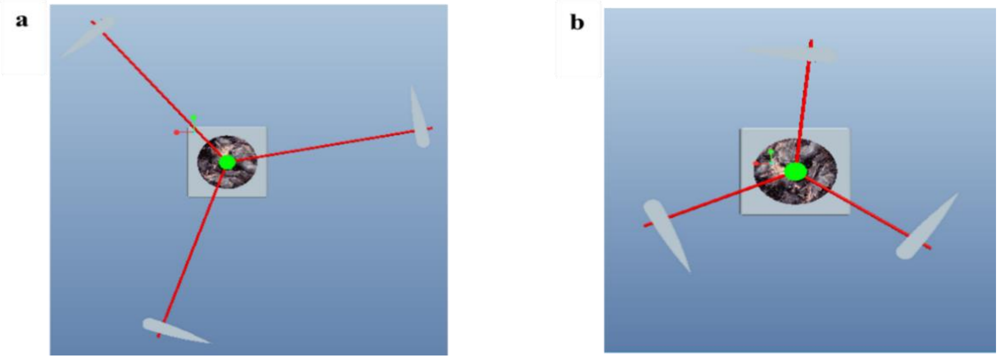

Figure 21: Monoplane VAWT with (a) 0.5 Solidity (b) 0.75 Solidity

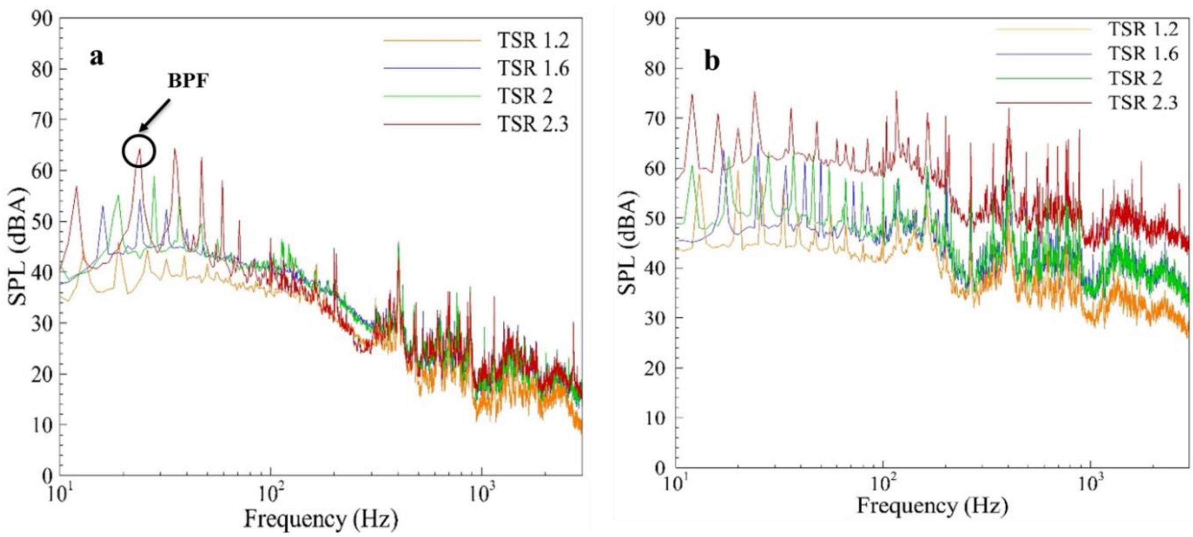

Figure 22: Frequency Spectrum of Monoplane VAWT at (a): 0.5solidity (b): 0.75 solidity

4.2.2. Tip Speed Ratio (TSR)

Tip Speed Ratio (λ) is the ratio of the rotor radius and rotational speed of the turbine to the flow velocity. TSR ($\lambda = \omega R/U$) is a nondimensional number, ω is rotation speed which is in rad/sec, R is rotor radius which is in m and U is flow velocity which is in m/s. The results show that when the TSR increases the noise generated by the monoplane VAWT also increases as shown in figure 22 and figure 23a. Four different TSR ratio has been studied ($\lambda = 1.2, 1.6, 2, 2.3$) along with the same solidity of 0.5. From the results, it can be suggested that for the reduction of sound the TSR should be low. The reduction in the sound amplitude is average 9dB if the TSR reduces from 2.3 to 1.2.

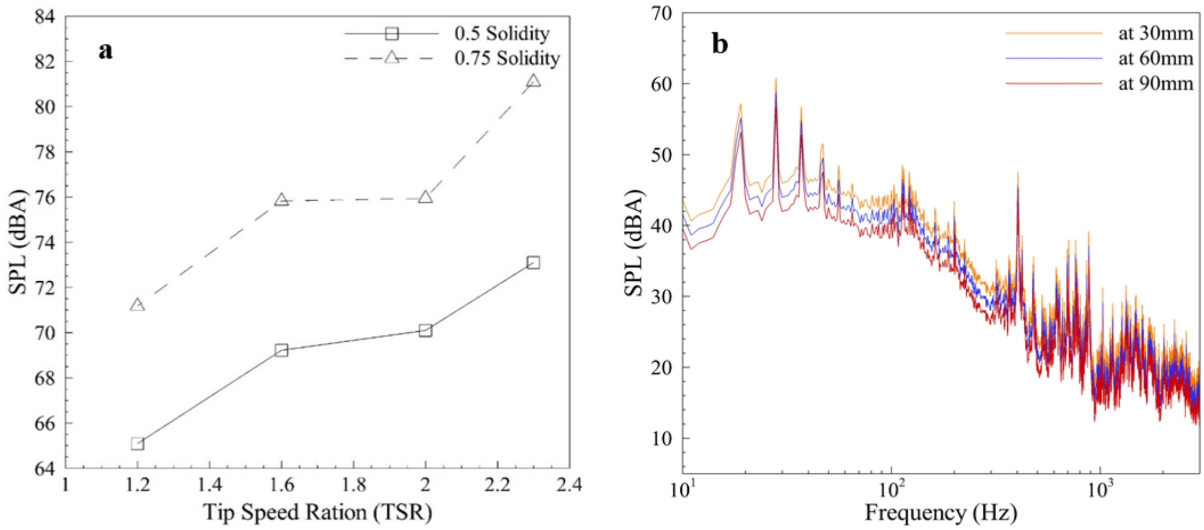

Figure 23: Monoplane VAWT (a) TSR vs SPL (b) Frequency Spectrum at axial distance 30, 60, and 90mm at 2 TSR

4.2.3. Effect of Distance between Source and Receiver

The spacing effects in figure 23b show that when the receiver moves axially away from the source there is a change in SPL of the turbine. Three different distances have been studied (x = 30, 60, 90 mm) along with the same solidity of 0.5. It is concluded that by moving away from the source, the SPL decreases but the frequency of the tonal peaks for every distance remains the same. All the first tonal peaks are at 25 Hz and the average decay rate of SPL remains constant at approximately 2.1dB at the given distances.

4.3. Biplane VAWT

A new design of VAWT is introduced in which two blades are installed on a single strut (3*2 = 6 blades). Every blade in the turbine was manufactured by two airfoils. Experiments were performed on six different distances (0.1, 0.17, 0.24, 0.25, 0.26, 0.29 m) at the frequency range of 3000 Hz.

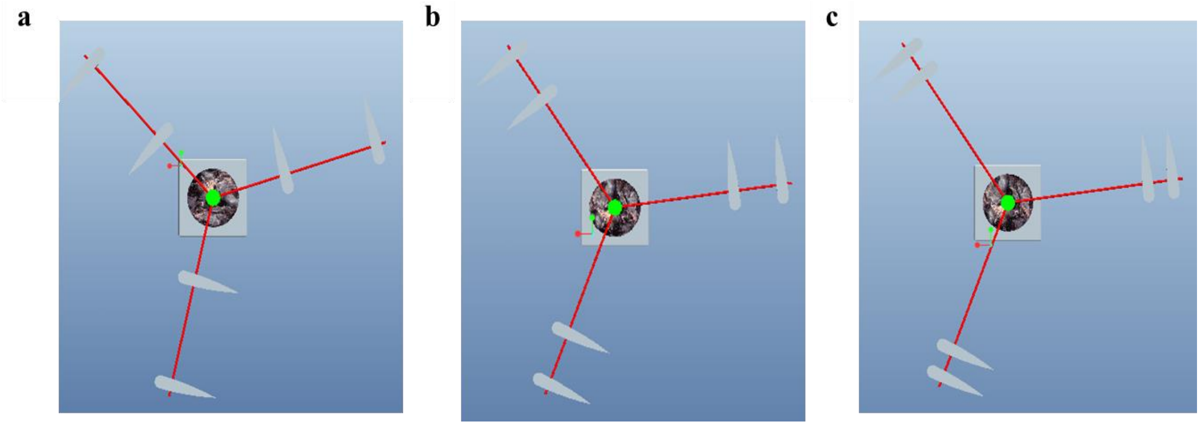

Figure 24: Biplane VAWT with spacing (a): 70% (b): 21% (c): 14%

4.3.1. TSR and Spacing Effect

The tip speed ratio is one of the most important parameters in the acoustics of VAWT. As described in the monoplane VAWT, four different TSRs were studied from the range of 1.2 to 2.3. Mohamed et al. [41] concluded in his study that an increase in TSR raises the noise. Different experiments were performed on the different spacing between the blades. However, the solidity will be remained constant at 0.5 for all the cases because as discussed in monoplane VAWT low solidity cause less noise. By introducing space between the blades, it will affect the noise generated from the blades. Therefore, different experiments were performed by introducing space between the blades.

The frequency spectrum of each spacing is shown in figure 25 and figure 26. As seen from the figures by decreasing the spacing the noise starts to reduce but there was a point after which the noise starts increasing again. This point is shown in figure 27 depicting the optimum point where the noise is minimum. Biplane VAWT has a positive impact on the domestic area at low TSRs. The reason is that there should be some angle between the first and second blades, due to which when flow strikes with the first blade, the wakes are generated representing eddies [42].

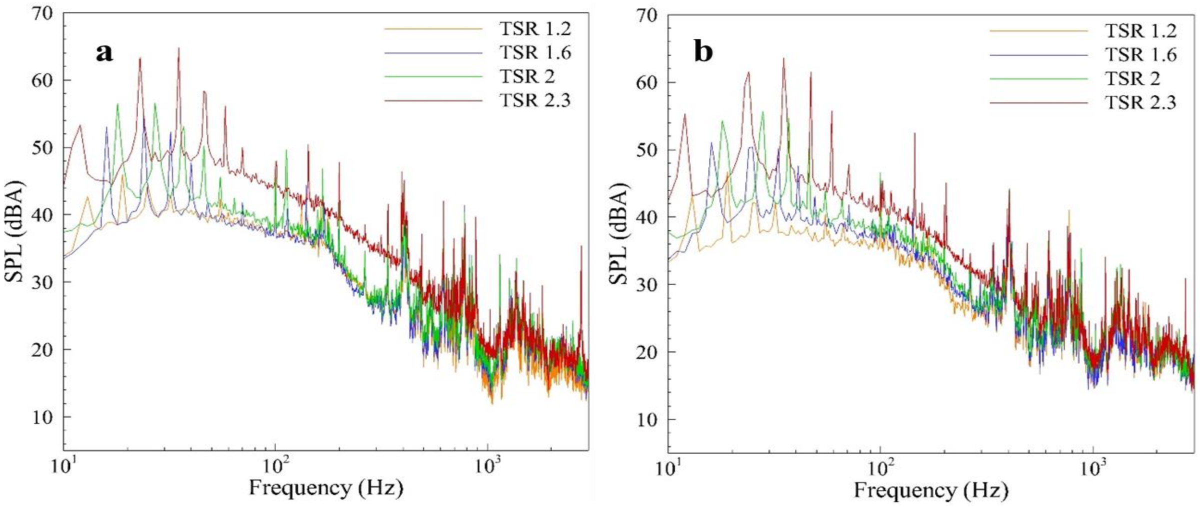

Figure 25: Frequency Spectrum of Biplane VAWT at spacing (a): 70% (b): 45.5%.

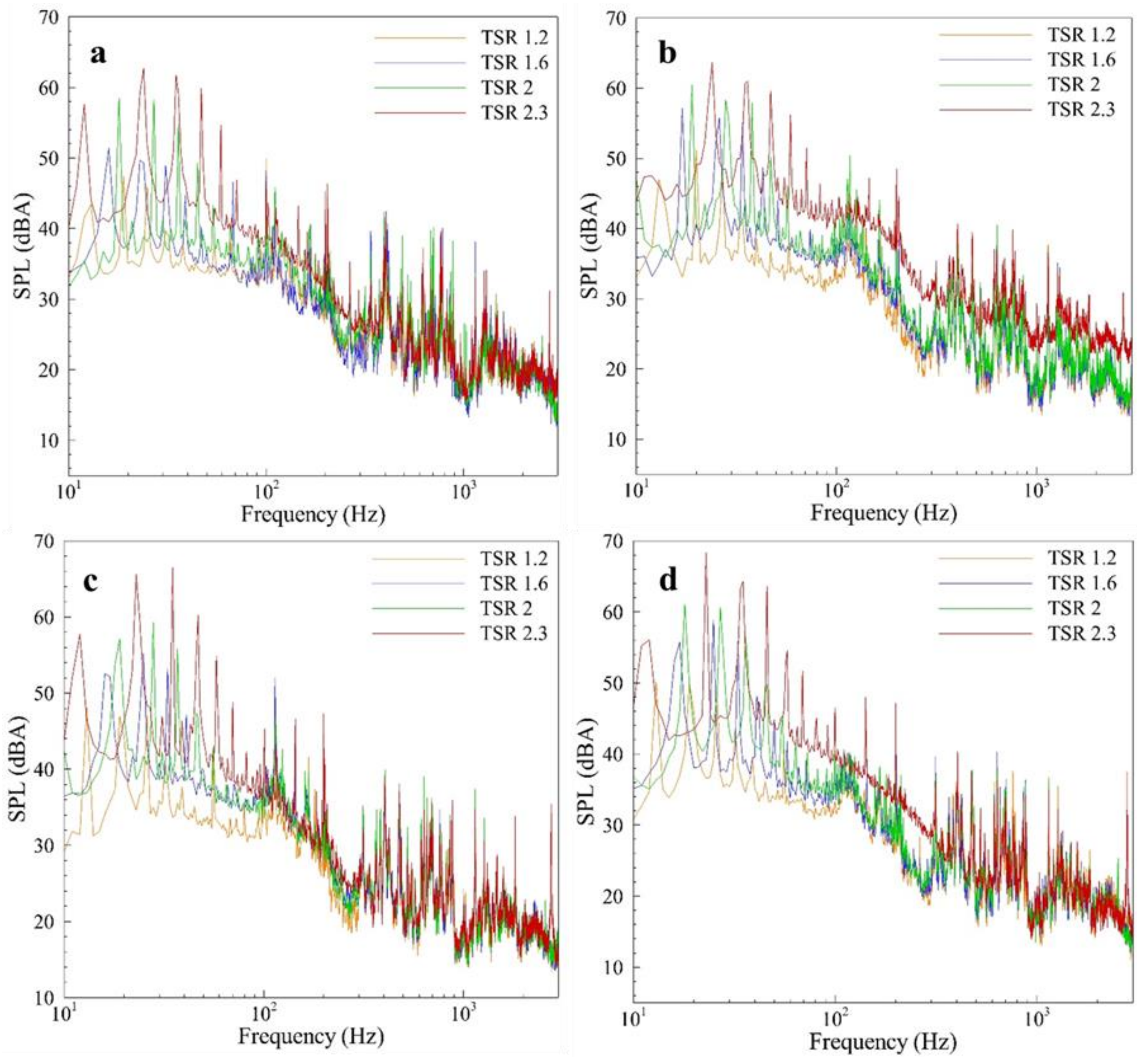

Figure 26: Frequency Spectrum of Biplane VAWT at spacing (a): 21% (b): 17.5% (c): 14% (d): 3.5%

When the spacing between the blades was 70% of the chord length, the eddies generated from the frontal blade interact with the trailing blades which cause the increase in the intensity of eddies due to which there is more flow separation in the second blade. Hence, due to the separation in flow, more noise will be generated. At an optimum point, 21% spacing of blades, the eddies generated from the upfront blade do not interreact with the trailing blades due to the position and angle of the blades. Thus, eddies lose their intensity due to no flow separation in the second blade resulting in less amount of noise compared to the 70% spacing. After the 21% spacing, the sound starts increasing again because of the frontal area as the blades move closer the frontal area is increases and more noise produces.

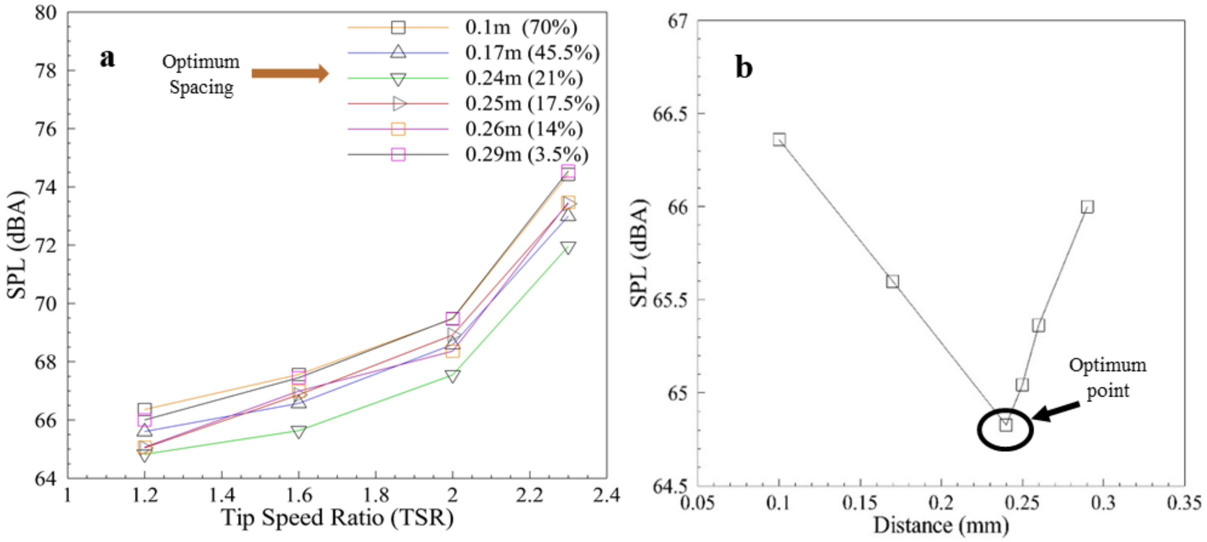

Figure 27: Biplane VAWT (a) TSR vs SPL at different spacing (b) Distance vs SPL at 1.2 TSR

4.4. Tandem VAWT

In the current study, the author aimed to reduce the noise generated from the VAWT blades by changing the arrangement of the blades in tandem form. The new design consists of two blades of the NACA-0012 profile. This new design of the turbine was used with different spacing of 20%, 60%, and 90% as shown in figure 28.

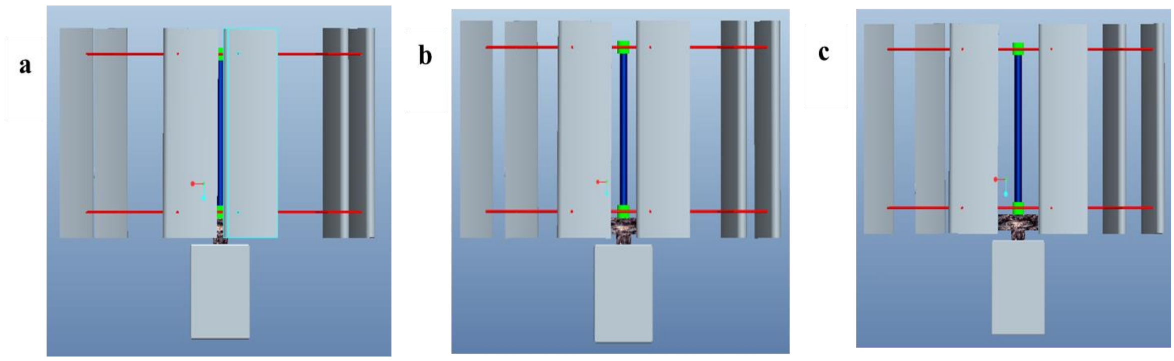

Figure 28: Tandem VAWT with spacing (a): 20% (b): 60% (c): 90%

4.4.1. TSR and Spacing Effect

Different experiments were performed on different TSR with different spacing between the blades. The spacing parameters were taken from the study of Mohamed [43]. He performs different 2d simulations on the VAWT by the spacing between the blades. In the study of tandem arrangement, the TSR effect was studied. Four same TSR were taken from range 1.2 to 2.3 with the same solidity of 0.5. Solidity was kept constant because it is a very important factor in the turbine aeroacoustics as well as aerodynamic performance, if the solidity is high it will cause a strong pressure difference over the blades. The frequency spectrum of the Tandem VAWT at different TSR can be seen in figure 29 and figure 30. When the space between the blades was 20%, the more noise is generated as compared to 60% and 90% due to the flow separation from the first and second blades. In 20% spacing, the eddies of the first blade influence eddies on the second blade due to which the more noise was produced but in 60% spacing there will be some shedding and angle difference in such a way that the eddies of the first blade do not interreact with the second blade hence, less noise was produced as compared to 20% of spacing. After the 60% spacing, there was a very small change in the noise which is almost negligible. From the graphs, it can be seen that there is low noise when the TSR is low. Hence, TSR has a great impact on noise generation.

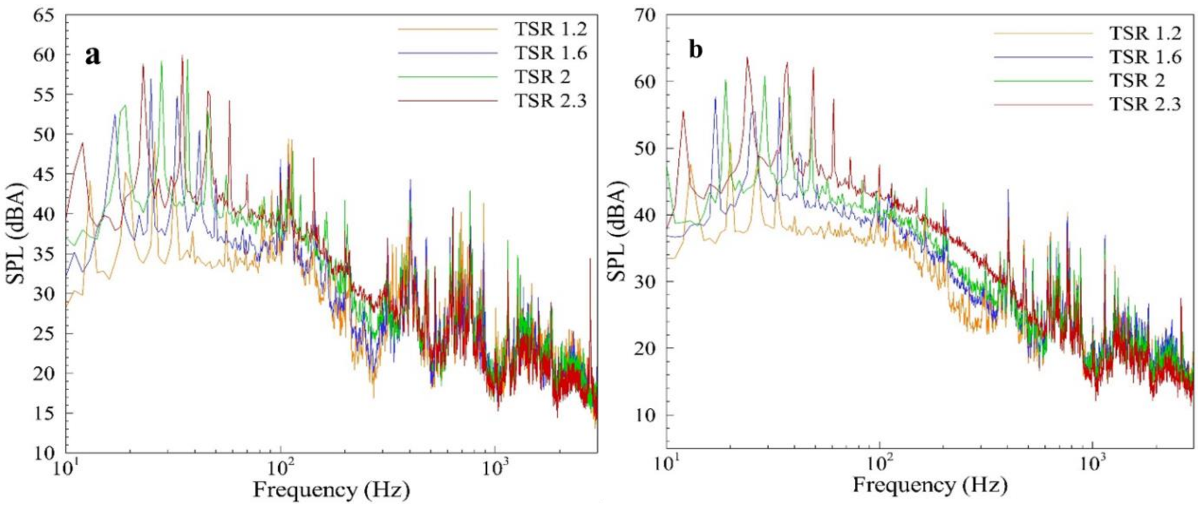

Figure 29: Frequency Spectrum of Tandem VAWT with spacing (a): 20% (b): 60%

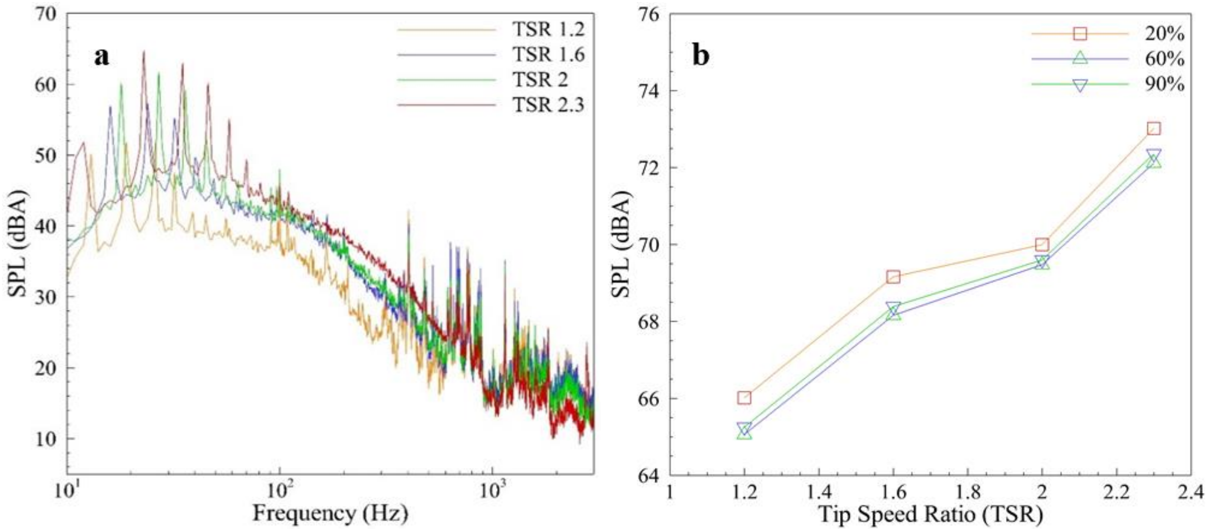

Figure 30: Tandem VAWT (a) Frequency Spectrum with 90% spacing (b) TSR vs SPL

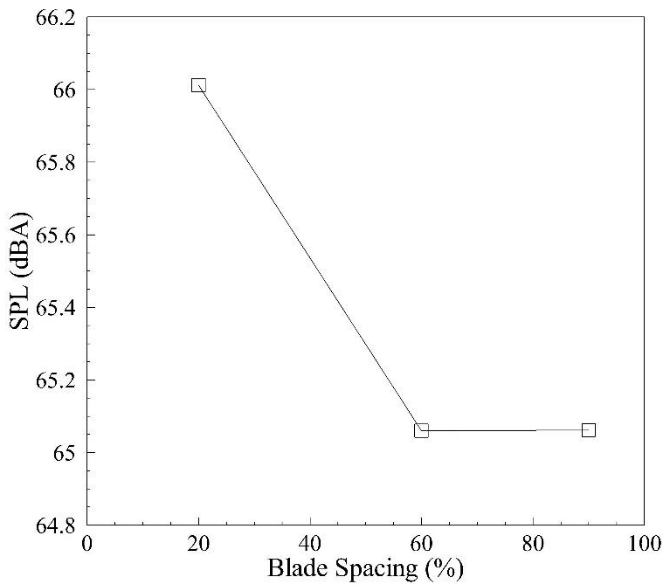

Figure 31: Blade Spacing vs SPL (Tandem VAWT)

Chapter 5: Conclusions

Vertical Axis Wind Turbines like Darrieus rotors are the most common turbines which are used on domestic buildings due to their compact and adaptive design. Hence, it is important to address the noise pollution of the VAWT. A new design of VAWT is introduced in this study to reduce noise generation. This is the first study on the experimental aeroacoustics noise generated from the biplane and tandem VAWT. The effect of solidity, the spacing between the blades, and TSR was studied in this paper considering the NACA-0012 profile for Biplane and Tandem VAWT blade arrangements. The noise calculations were done using the linear acoustic array. The results of the study showed that by increasing the TSR, the noise also increases for all the arrangements either it is monoplane, biplane, or tandem.

- In monoplane VAWT, an increase in solidity from 0.5 to 0.75, the noise was raised with approximately 7.99 dBA. Hence, it is concluded that to reduce the noise generated from the monoplane VAWT rotor should work on low solidity.
- Biplane VAWT is the best-suited turbine because it generates less noise as compared to conventional VAWT with a difference of 3.22 dBA at 0.5 solidity. In biplane VAWT results indicated that when the spacing between the blades increases the noise increases. At the spacing of 21% of the chord length of the blade, the minimum sound is generated. After that point sound increases again.
- However, in tandem VAWT different experiments were performed with different spacing and the results show that at 60% spacing the minimum sound is generated as compared to 20% and 90% with the solidity of 0.5 and at different TSRs. Moreover, by comparing the results of tandem with the conventional VAWT, the new design reduces the sound by almost 1.1 dBA.

Chapter 6: Future Recommendations

There are few additional works that can be done on the experimental setup and introducing some new features in this work

1. In future work the effect of rotor solidity can be taken into consideration and the type of airfoil and the number of blades can be changed on same VAWT to find a way through to minimize the noise sources.
2. For the better understanding of flow separations or the aerodynamic noises PIV should be performed.
3. By upgrading the microphone array to 3D source localization and identifying discrete noise sources during dynamic stall can provide us very useful information regarding design changes for noise minimization.

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