AERODYNAMICS AND PERFORMANCE OF VARIABLE-PITCH VERTICAL-AXIS TURBINES AT LOW TIP-SPEED RATIOS

AARON BASIL RAJ A/L SURESH RAJ

UNIVERSITI SAINS MALAYSIA

2021

AERODYNAMICS AND PERFORMANCE OF VARIABLE-PITCH VERTICAL-AXIS TURBINES AT LOW TIP-SPEED RATIOS

by

AARON BASIL RAJ A/L SURESH RAJ

Thesis submitted in fulfilment of the requirements for the Bachelor Degree of Engineering (Honours) (Aerospace Engineering)

June 2021

ENDORSEMENT

I, Aaron Basil Raj a/l Suresh Raj hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

(Signature of Student)

Date: 8 July 2021

(Signature of Supervisor)

Date: 9 July 2021

(Signature of Examiner)

Date: 9 July 2021

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date: 8 July 2021

ACKNOWLEDGEMENT

I have received a great deal of support, advice and encouragement from many throughout my journey in this research.

First of all, I would like to express my sincerest appreciation to Assoc. Prof. Dr. Ahmad Zulfaa Mohamed Kassim, my final year project supervisor, for guiding me throughout my final year project journey. This thesis would not have been possible without the guidance, sacrifice and encouragements from him.

I would also like to thank my final year project examiner Dr. Norizham Bin Abdul Razak for his constructive advice that led to better clarity and a higher technical competency in improving the quality of the research. I would also like to thank the School of Aerospace Engineering, Universiti Sains Malaysia for allowing me and setting up a conducive platform for me to complete this research project.

Finally, I must express my gratitude towards my parents, grandparents, family and friends for their continuous support and encouragement throughout my study in Universiti Sains Malaysia and the process of completing this thesis. This accomplishment would not have been possible without the combined support from all of them.

AERODYNAMICS AND PERFORMANCE OF VARIABLE-PITCH VERTICAL-AXIS TURBINE AT LOW TIP-SPEED RATIOS

ABSTRACT

The shift to renewable energy is imminent to aid the world's effort to reduce its total carbon footprint and fight off global warming. Wind and hydrokinetic energy have great potential to replace the depleting reserves of fossil fuels. With its scalability and omnidirectional advantage, vertical-axis turbines are a great renewable energy source for off-grid and rural areas. Although the vertical characteristics of the turbine look promising, it is known to have far lower performance than its horizontal counterpart. This research investigates the detailed aerodynamic study of lift and drag contribution on the turbine blades with variable-pitch blade through numerical simulation via an open-source software called Qblade. The problems to be investigated in this research are the effects of pitch angle on the aerodynamic contribution of the blades and the variable-pitch model to improve performance over various operating ranges. It is suggested that applying pitch angle to the blade at a controlled amount can help maintain a constant steady angle of attack, which can be altered to extract the most performance. The effects of blade pitching would be studied to determine the instantaneous aerodynamic loadings, the tangential and normal forces while ultimately referencing the average power coefficient, C_P for overall performance. Variable-pitch blade will be employed in this study to compare and determine the benefit and drawback of the pitching method for vertical-axis turbine performance. The investigation would be carried out by a series of numerical simulations of a single-bladed Darrieus turbine in Qblade using the Lifting Line Free Vortex Wake (LLT) module. A single blade is chosen to solely

study the complete aerodynamic loading without compromising the effects of multiple blades and complex wakes. The blade will be modelled locally in Qblade's Blade Designer module with a NACA 0018 airfoil profile and experimentally tested 360º extrapolated airfoil polar data to ensure realistic and accurate data. Validation studies are then carried out by comparing the simulated results from Qblade to Computational Fluid Dynamics (CFD) solution and experimental tests to ensure the method and model used in the simulation are accurate and trustworthy. The data obtained from Qblade is then processed in MATLAB to observe the aerodynamic loads on the blade and the aerodynamic contribution to the power produced in a turbine rotation. A fine-tuned variable-pitch blade will be created through MATLAB and implemented via Simulation Input Files in a turbine model in Qblade. LLT simulation would be carried out for low tip-speed ratios of 0.75, 1.0, 1.6, 2.0, and 2.5, allowing us to observe the impact of different tip-speed ratios on variable-pitch blade.

AERODYNAMICS AND PERFORMANCE OF VARIABLE-PITCH VERTICAL-AXIS TURBINE AT LOW TIP-SPEED RATIOS

ABSTRAK

Peralihan ke tenaga boleh diperbaharui akan segera berlaku untuk membantu usaha dunia mengurangkan jejak karbonnya dan melawan pemanasan global. Tenaga angin dan hidrokinetik berpotensi besar untuk menggantikan simpanan bahan bakar fosil yang akan habis. Dengan kelebihan skalabiliti dan kebolehan berfungsi tanpa kira arah angin, turbin paksi menegak adalah sumber tenaga yang boleh diperbaharui untuk kawasan bandar dan luar bandar. Walaupun ciri - ciri menegak turbin kelihatan berpotensi, ia diketahui mempunyai prestasi yang jauh lebih rendah daripada turbin paksi mendarat. Kajian ini menyiasat kesan aerodinamik terperinci sumbangan daya angkat dan daya seret pada bilah turbin dengan sudut laras pemboleh ubah melalui simulasi berangka mengunakan perisian sumber terbuka bernama Qblade. Isu yang akan dikaji dalam penyelidikan ini adalah kesan sudut laras pada sumbangan aerodinamik bilah turbin dalam meningkatkan prestasi dalam pelbagai rentang operasi. Adalah dicadangkan bahawa melaras sudut pada bilah turbin pada kadar terkawal boleh bantu menjaga kadar sudut serangan yang boleh dikawal untuk memperolehi prestasi turbin yang terbaik. Kesan sudut laras akan dikaji untuk menentukan muatan aerodinamik sesaat, daya tangen dan normal sambil merujuk pada prestasi keseluruhan dalam bentuk pekali prestasi, C_P. Sudut laras pemboleh ubah digunakan dalam kajian ini untuk membandingkan dan menentukan manfaat dan kelemahan kaedah tersebut dalam prestasi turbin paksi menegak. Siasatan akan dijalankan oleh beberapa siri simulasi berangka turbin Darrieus beribilah satu dalam perisian Qblade menggunakan modul ‘Lifting Line Free Vortex Wake’

(LLT). Turbin berbilah satu dipilih untuk mengkaji beban aerodinamik tanpa menjejaskan model kepada kesan bila-pelbagai dan ‘wake’ yang kompleks. Bilah turbine akan dimodelkan secara tempatan dalam modul ‘Blade Designer’ Qblade dengan profil airfoil NACA 0018 dan data polar yang diekstrapolasi 360° untuk memastikan data yang realistik dan tepat. Kajian pengesahan kemudian dijalankan dengan membandingkan keputusan simulasi dari Qblade dengan solusi Komputasi Dinamik Bendalir (CFD) bersama ujian eksperimen bagi memastikan kaedah dan model yang digunakan dalam simulasi adalah tepat dan boleh dipercayai. Data yang diperoleh dari Qblade kemudian diproses dalam perisian MATLAB untuk memerhatikan beban aerodinamik pada bilah turbin dan sumbangan aerodinamik terhadap daya yang dihasilkan dalam putaran turbin. Sudut laras pemboleh ubah akan dihasilkan melalui MATLAB dan dilaksanakan melalui Fail Input Simulasi dalam model turbin di Qblade. Simulasi LLT akan dilaksanakan untuk nisbah kelajuan hujung rendah 0.75, 1.0, 1.6, 2.0, dan 2.5, untuk memerhatikan kesan nisbah kelajuan hujung yang berbeza pada sudut laras pemboleh ubah dari segi

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

C_P	Power coefficient
β	Pitch angle $[deg]$
θ	Azimuthal position $[deg]$
H	Blade Span $[m]$
N	Number of blades
c	Blade chord $[m]$
D	Rotor diameter $[m]$
σ	Turbine solidity
V_∞	Freestream velocity $[ms^{-1}]$
ρ	Flow Density $[kgm^{3}]$
μ	Flow Dynamic viscosity $[kgms^{-1}]$
Re	Freestream Reynolds number
λ	Tip-speed ratio
α	Angle of attack $[deg]$
C_L	Lift coefficient
C_D	Drag coefficient
C_T	Tangential force coefficient
C_{TL}	Lift component of tangential force coefficient
C_{TD}	Drag component of tangential force coefficient
C_N	Normal force coefficient
C_{NL}	Lift component of normal force coefficient
C_{ND}	Drag component of normal force coefficient
C_Q	Torque coefficient
ω	Turbine blade angular velocity $[rad\ s^{-1}]$
F_T	Tangential force $[N]$

F_N	Normal force $[N]$
F_{Tavg}	Average tangential force $[N]$
Q	Torque $[Nm]$
P	Power output $[W]$
S	Rotor swept area $[m^2]$

LIST OF ABBREVIATIONS

VAT	Vertical-axis Turbine
HAT	Horizontal-axis Turbine
BEM	Blade Element Method
DMST	Double Multiple Streamtube Model
LLT	Lifting Line Free Vortex Wake Method
CFD	Computational Fluid Dynamics

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

This chapter introduces the primary motive of this research and the overview of vertical axis turbines. The problems experienced by a vertical axis turbine at a low tip-speed ratio are explained, and a numerical simulation approach is undertaken to analyze the turbine and its performance.

1.1 Motivation

World energy usage is expected to increase by 50% by the year 2050, according to the U.S Energy Information Administration (EIA) (EIA, 2020). This massive growth is projected to be led by Asia and countries outside the Organization for Economic Cooperation and Development (OECD). This issue spells crisis as over 80% of our energy production is dependent on fossil fuels, which are non-renewable energy sources that are rapidly depleting. Over-reliance on fossil fuels is unsustainable and ecologically destructive, causing global warming to increase the temperature of the Earth where average temperatures have risen by about 1^{o} C. It has been observed that for every kilowatt-hour (kWh) of non-sustainable electricity generated, an average of 1689 grams of carbon dioxide equivalent of greenhouse gasses is emitted (Salleh et al., 2018). The particles emitted during energy production combined with the greenhouse effects pose a severe threat to humanity regarding health and wellbeing.

Many new renewable and sustainable energy sources were sought after to find a solution for the rising energy and pollution crisis. However, renewable energy usually comes with a lot of foreground and background costs, which are not favourable for developing countries. The cheaper labour and maintenance cost of running a fossil-fuel-powered generator carries more importance than the environmental impact on a small developing country. Despite the lower costs of such power stations, unsustainability and pollution factors call for more sustainable and eco-friendly alternatives. As such, the utilization of renewable energy sources is endorsed as substitutes for fossil fuels to meet the world's increasing demand for electricity with minimal environmental impact.

Malaysia is an industrialized market economy. Around 40% of Malaysia's revenue is generated from oil and gas export, so it is not surprising that fossil fuel would be the go-to method to power most of the nation. According to a survey from the National Energy Balance, 53% of the electricity generation is met by natural gas, 40% is met by coal and 7% by hydro (Abdullah et al., 2019). To promote renewable energy growth and applications, the Malaysian government launched The Renewable Energy Act 2011, which focused on renewable energy in electricity generation. Hydropower has been proposed to be the main contributor to the growth of renewable energy utilization in Malaysia because of its low cost and environmentally friendly nature.

Rural areas typically have less reliable access to the power grid linked to a large-scale renewable energy source such as hydro power due to their geographical location and population. Therefore, the limited energy consumption in such areas does not justify building more large-scale dams that produce hydropower for these rural areas. However, Malaysia and some Southeast Asian countries have numerous flowing rivers that can be used for small-scale vertical-axis hydrokinetic power generation. These generators could also help in off-grid projects that take up only a tiny amount of power and have little to no operational costs.

However, existing performance, efficiency and energy-to-cost ratio issues must be addressed before successfully implementing vertical axis turbines in general for both wind and hydropower. Betz's Law plays an essential part in turbine design. It states that only a limited amount of air can pass through a turbine at a time for the turbine to be functionally efficient, and an efficient turbine can only convert a small amount of energy in the wind to electrical power. Many research studies have been undertaken by many to improve and optimize vertical axis turbine efficiency and performance. In this research, an open-source turbine numerical analysis software called Qblade will be used to study the performance gains of a vertical axis turbine with variable-pitch blades at a low tip-speed ratio. A numerical simulation approach is undertaken to reduce the cost and time in analyzing the problem at hand. At the same time, it also maintains a reasonable degree of accuracy and reliability in predicting the behaviour and performance of the turbine.

1.2 Overview

Wind and hydrokinetic power are promising directions in renewable and sustainable energy for a cleaner, greener planet. Vertical axis turbines are known for their scalability and omnidirectional characteristics, suitable for urban and rural applications. However, they lack in terms of performance and efficiency when compared to their horizontal counterpart. There are two types of vertical axis turbines, the lift-driven Darrieus and the drag-driven Savonius turbines. The Darrieus-type turbines operate based on the principle of lift generated by blades profiled to the shape of airfoils. The Savonius type turbines operate on the principle of drag and are relatively inefficient compared to the Darrieus type. Many configurations are available for a Darrieus type turbine; a straight-bladed or H-type turbine, a Troposkein turbine and the Helical turbine. In this research, the aerodynamics of the H-type turbine is studied, and performance is analyzed, with the reason of reduced complexity in analyzing a straight blade. The main difference between a vertical-axis and a horizontal-axis turbine is the ability to operate irrelevant of wind direction. Vertical axis turbines are also capable of functioning in a higher turbulent environment than a horizontal axis turbine.

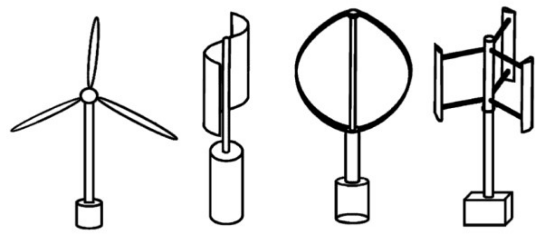

Figure 1.1 Illustrations of horizontal and different types of vertical axis turbines.

The performance and aerodynamic analysis of an H-type Darrieus turbine begin with the blades. The rotating blade encounters wind in a complete 360^o direction. The velocity vectors of the wind speed and horizontal speed add up to produce a resultant velocity, W. The turbine blades are subjected to various effective angles of attack in a single rotation, caused mainly by the freestream velocity and rotational velocity vectors. The ratio between the wind and rotational velocity vector (tip-speed ratio, λ) affects the angle between the resultant velocity and the blade chord line. The effective angle of attack is thus dependent on the tip-speed ratio and azimuthal angle. The flow over the blades would then effectively produce lift ($\mathbf{L}$) and drag ($\boldsymbol{D}$), forces based on the instantaneous angle of attack and the type of airfoil used by the blade. The lift and drag forces can then be resolved into tangential force $\boldsymbol{F_T}$ that is parallel to the chord line, and normal force $\boldsymbol{F_N}$ which is perpendicular to the chord line. The tangential force is the force that drives the turbine and generates torque, which then creates power. The power produced by the turbine is denoted as the coefficient of power, $\boldsymbol{C_P}$, derived from the blade torque coefficient $\boldsymbol{C_Q}$.

1.3 Problem Statement

The main problems that are to be ventured in this research are listed in 3 points below. These problem statements will serve as the focal point of this research to understand the dynamics and performance of turbines at a low tip-speed ratio with the impact of variable-pitch blade. The listed issues are illustrated further in the section that follows.

1) The changing angle of attack relative to tip-speed ratio causes the flow to separate and stall at lower speeds when the angle of attack is too high. This causes large amounts of performance hindering drag.

2) During this period of low tip-speed ratio, the presence of this large amount of drag causes the turbine to experience loss in efficiency and performance.

3) One method to help increase performance in this region is by actively pitching the blade to compensate for the extreme angle of attacks of the blade at a low tip-speed ratio.

A turbine experiences various tip-speed ratios in its cycle before reaching its designed optimal tip speed. During this low tip-speed ratio period before reaching the optimal region, the turbine experiences a considerable loss in performance and efficiency. This optimal performance region is crucial as most vertical axis turbines experience low tip speeds when the freestream wind is inconsistent. Hydrokinetic vertical axis turbines also tend to rotate at a low tip-speed ratio at most times.

The variation in the angle of attack following tip-speed ratio could allow the flow on the blade to separate and stall at lower speeds when the effective angle of attack is high, creating a high amount of drag that hinders the overall performance.

This characteristic of vertical axis turbines makes them less viable when compared to a horizontal axis turbine in terms of performance and efficiency.

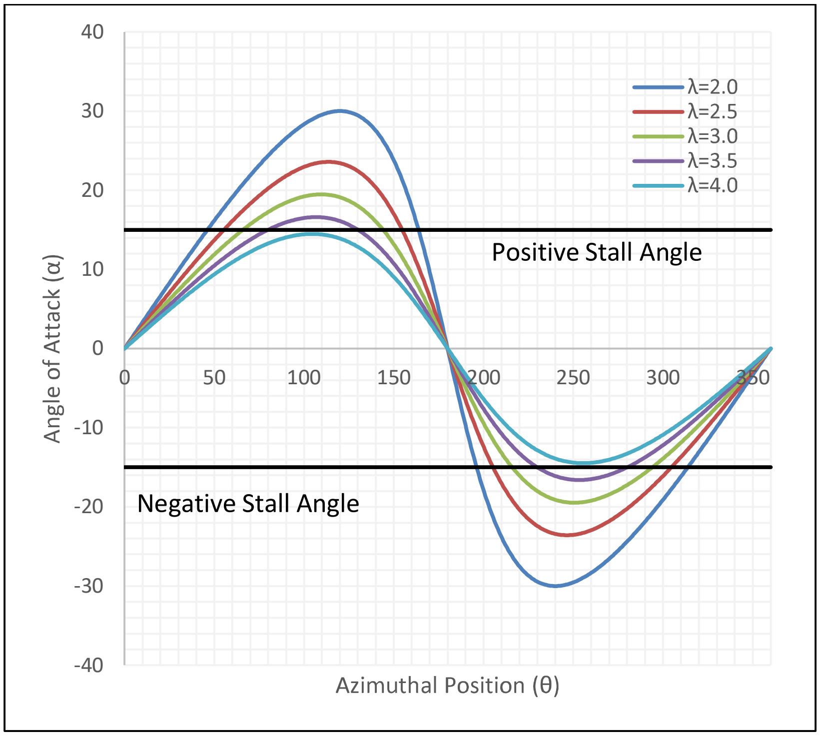

Figure 1.2 Angle of attack at various tip-speed ratios (NACA 0018)

One method to overcome the excessive flow separation and stalling of the blades of vertical axis turbines is by actively pitching the blade to compensate for the extremes in blade angle of attack at a low tip-speed ratio. This method can be called as Variable-pitch blade method as the blade pitch will vary across the azimuthal position. The presence of a blade pitch could ‘trim’ the effective angle of attack of the blade to a said angle to ensure that additional performance is gained by suppressing the drag caused by flow separation and blade stalling. However, the varying blade pitch has to be controlled based on tip-speed ratio, flow speed, and the local Reynolds number on the blade to ensure that the optimal angle of attack is maintained. Doing so causes the blade not to stall, ensuring that the overall effect doesn’t negatively affect the turbine performance.

1.4 Objectives

The aim of this research is listed below in correlation to the problem at hand. Each research objective signifies a goal to solve the problem stated in the previous section.

1) To study the turbine dynamics in terms of aerodynamic contribution on tangential coefficient at a low tip-speed ratio that leads to a large amount of drag.

2) To observe the performance and efficiency of the turbines at various low tip-speed ratio

3) To create a turbine model with variable-pitch blade that can improve turbine performance at a low tip-speed ratio and observe the performance and efficiency gains.

This research aims to study the aerodynamic contribution of the blades on tangential coefficient and overall power produced at low tip-speed ratios with variable-pitch blade through numerical simulation via an open-source turbine analysis tool named Qblade. In addition, the instantaneous lift and drag forces will be studied to observe their contribution to the tangential force at low tip-speed ratios and the aerodynamic behaviour of the blades when variably pitched.

The pitch angles will be generated and optimized based on the unmodified vertical axis turbine of identical design in MATLAB. The effects of pitch angles on turbine performance are analyzed by running different pitch angles as inputs in Qblade. This data would be read into Qblade by custom Simulation Input Files to allow for a refined blade pitch at specific azimuthal intervals.

1.5 Research Scope

The numerical model will be built in Qblade using input files, necessary input parameters and a suitable algorithm to simulate the flow at a given condition. Qblade uses a lifting line theory and vortex modelling method to predict the wake and forces acting on and off a turbine blade with a reliable amount of accuracy. However, using these lower fidelity methods doesn't allow for more discrete flow visualization to better help understand the flow behaviour over the blade. For variable-pitch blade, a simulation input file is used in addition to the pre-existing numerical input options available in Qblade itself.

The configuration of the vertical axis turbine studied is a straight H-type single-bladed Darrieus turbine, as mentioned previously. This configuration was chosen to observe the individual aerodynamic characteristics of a vertical axis turbine blade without much interruption from the wake generated. Moreover, since the flow condition studied is at a lower tip-speed ratio, the effects of wake on turbine aerodynamic performance will be minimal. The wake would end up further than the blade could intercept. The scale, size, radius and other design parameters of the vertical axis turbine model are described in the Methodology chapter.

The research focuses on investigating the performance impact of a variably pitched turbine blade at low tip-speed ratios in terms of its aerodynamic contribution to the blade's tangential coefficient. The optimum pitch angle of the blade was decided after testing for various angles of attack, and the stall angle, where the lift is supposedly at its maximum, is chosen due to the higher capability of the blade at this orientation to produce the most power. Research has shown that applying blade pitch angle can improve turbine performance efficiency while not compromising on added complexity and manufacturing costs (Bianchini et al., 2015).

A real-life vertical axis turbine would experience a multitude of angular acceleration as the wind speed keeps changing. The blades start from a static condition and reach its terminal velocity. However, for this research, a steady-state is assumed where the turbine is assumed to be rotating at a constant speed with no angular acceleration. This would result in an analysis of a continuous tip-speed ratio with consistent performance at that range.

Similar to the tip-speed ratio of the turbine being fixed, the moment of inertia of the turbine is also constant for this research. A turbine with heavier blades would require more kinetic energy to spin the turbine up to speed when compared to a lighter turbine. Thus, having a consistent moment of inertia with similar weight distribution is crucial in ensuring a reliable result.

A low fidelity simulation technique would allow for a rapid design test of vertical axis turbines at the cost of lower result accuracy. However, the results obtained using Qblade will be validated with CFD techniques with experimental data to ensure the model's accuracy and simulation are within a tolerable and reasonable range.

1.6 Thesis Layout

The outline of this thesis is as follows: Chapter 2, Literature Review, presents the background of fundamental concepts of this research and reviews previous literature on vertical axis turbine dynamics and performance simulations and recent modifications in blade pitch methods to improve efficiency and performance. An open-source software, Qblade, was used to simulate the dynamics and performance of the turbine, taking into account the fundamental theories, equations and assumptions. The simulation set-up processes and the Variable-pitch blade approach are clearly described in Chapter 3, Methodology. Chapter 4, Results and Discussion, presents the simulation analysis for both the pitched and unpitched turbine models, discussing the effects of variable-pitch blade, performance impacts and the feasibility of the results obtained. The final chapter, Chapter 5, Conclusion and Recommendation, presents the conclusions and recommendations for further future work.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the literature review and background of the research. The chapter is split into four subsections: the fundamental of turbine design, the aerodynamics of the turbine blades, the effects of blade pitch on vertical axis turbine performance, and the background on the simulation software Qblade. The first two subsections explain the fundamentals of turbines, aerodynamics, and a succinct background into the concepts and equations used. Subsequently, the importance of blade pitch on turbine performance is explained in detail, followed by the operational standpoint of Qblade and the simulation methods used.

2.1 Fundamental of Turbine Design

The H-type Darrieus turbine blades have no taper or twist, making it a very suitable device for manufacturing. Research on comparing the aerodynamic efficiency of both vertical axis and horizontal axis wind turbines has been made a good argument in terms of parameters such as tip-speed ratio (λ), effects of Reynolds number (Re), torque characteristics (τ), effects of airfoil shape, effects of solidity (σ), and effects of wind shear. Reynolds number notably affects the lift coefficient C_L, drag coefficient C_D and the accuracy of the numerical analysis results.

2.1.1 Solidity

Designing for the solidity of a vertical axis turbine involves careful consideration and compromises. High-solidity vertical axis turbines achieve peak power early, producing more torque and power at a low tip-speed ratio benefiting the self-starting capacity of the turbine.

However, their efficiency drops quickly after reaching the optimum tip-speed ratio, leaving a sharp peak and a narrow operating region. In contrast, low-solidity vertical axis turbines prefer a high tip-speed ratio, with a flatter performance curve, translating into a more consistent power delivery across the board and a gentler slope (Parker & Leftwich, 2016). Therefore, the optimal design for vertical axis turbine solidity should consider the operating conditions of the fluid regime. However, high-solidity rotors benefit from low rotor noise, the stability of torque ripple and output power. On the other hand, low-solidity rotors are more sensitive to rotor mass-imbalance vibration, resulting in higher operating and maintenance costs. In the context of the blade solidity equation, varying the number of blades or the size of the blade chord can change the solidity. However, altering the blade chord also induces a change in the vertical axis turbine aspect ratio, blade Reynolds number, and blade flow curvature, all of which have complex influences on vertical axis turbine performance and aerodynamics.

2.1.2 Number of blades and type of airfoil

Raciti Castelli et al., (2011) compared vertical axis turbine configurations with three, four, and five blades and found that the three-bladed VAT has the best performance. The results are consistent with the study of Liang et al., (2018) and Sabaeifard et al., (2012). Liang Li, (2018) added that a three-bladed vertical axis turbine was singled out as the optimal configuration because it has good self-starting capabilities, is structurally non-directional, has a better choice of fabrication technique, and has better structural dynamics. Furthermore, the two-bladed vertical axis turbines have a higher annual generating capacity in high wind velocity regions. In contrast, the five-bladed vertical axis turbines are preferred at low wind velocity areas. The number of blades depends on the application and the conditions the turbine would experience.

When it comes to airfoil thickness, NACA 0018 performed well and generated a maximum peak power coefficient (Cp) for different tip-speed ratios compared to other airfoils (De Tavernier et al., 2018). The thickness of the airfoil plays a vital role in the generation of lift forces in a Darrieus turbine; as the azimuthal angle changes, the flow tends to separate if the thickness is high and the local Reynolds number is low, resulting in dynamic stall. Abd Aziz et al,. (2014) concluded in their study that a NACA 0015 airfoil performs better than a NACA 0012 airfoil under the same conditions with an optimal stall angle of 10° to 15° due to the added thickness at similar conditions. Thus, choosing a suitable airfoil based on the expected flow conditions could reduce these stall regions and positively impact overall turbine performance. Typically, a symmetrical airfoil is preferred for vertical axis turbines as the blade produces both positive and negative lift during a single revolution. This makes the symmetrical airfoil ideal in balancing the distribution of power throughout the complete revolution.

2.1.3 Aspect Ratio

Aspect ratio is the ratio between the square of the blade length to the blade's surface area. Brusca et al., (2014) showed in their research that the aspect ratio of the rotor plays a significant role in the design and performance of the turbine. Brusca et al., (2014) also showed that a lower aspect ratio is much more efficient than a larger one. The change in aspect ratio also changes the chord length, affecting the Reynold number, ultimately affecting the torque produced. This problem was also investigated by Stout et al., (2017) and discussed even more in terms of high Reynolds number by Armstrong et al., (2012).

2.1.4 Tip-speed Ratio and turbine wake

Tip-speed ratio is an essential parameter in the design of a vertical axis turbine. It determines the behaviour of the blade in terms of the angle of attack and the general flow over the blade of a turbine. Another critical aspect dependent on tip-speed ratio is the wake of the turbine, which affects the performance and aerodynamics of the blades. Parker & Leftwich, (2016) explained the effects of tip-speed ratio and Reynolds number on the turbine wake via wind tunnel testing. They were able to show that Reynolds numbers and tip-speed ratios show distinct, asymmetric wake behind the turbine model. The wake structure is strongly dependent on the tip-speed ratio while only varying slightly with the Reynolds number. The works of Battisti et al., (2016), Buchner et al., (2018) and Hohman et al., (2018) agree on the production of a more significant momentum deficit in the wake of vertical axis turbines for increasing values of tip-speed ratio.

Furthermore, experiments by Rezaeiha et al., (2018) have shown more substantial dynamic stall phenomena and more prominent vortices in the wake of a smaller tip-speed ratio turbine. Many computational studies also discuss the influence of tip-speed ratio on wake properties; some of them are, Zanforlin & Nishino, (2016), Nazari et al., (2018), and Rezaeiha et al., (2018). However, the wake size and formation are not as significant in studying turbine blade aerodynamics but must be considered during complete rotor analysis.

2.2 Fundamental aerodynamics of vertical-axis turbines

The two forces of lift, F_l and drag, F_d work in unison as the blade revolves and changes its azimuthal position, θ. The resolved forces create a rotational motion that is translated to tangential or thrust force, F_t. The other key component in the aerodynamics of the blades is the freestream velocity U_∞ and the rotational velocity component V perpendicular to the leading edge of the blade. The resultant velocity component W, plays a vital role as it will be taken into account to find the tangential force F_t. The angle between the rotational velocity component V and the resultant velocity component W, given as angle of attack α is affected by the tip-speed ratio λ and the azimuthal position θ. As mentioned previously, the tip-speed ratio is a significant parameter that governs the performance of the vertical axis turbine.

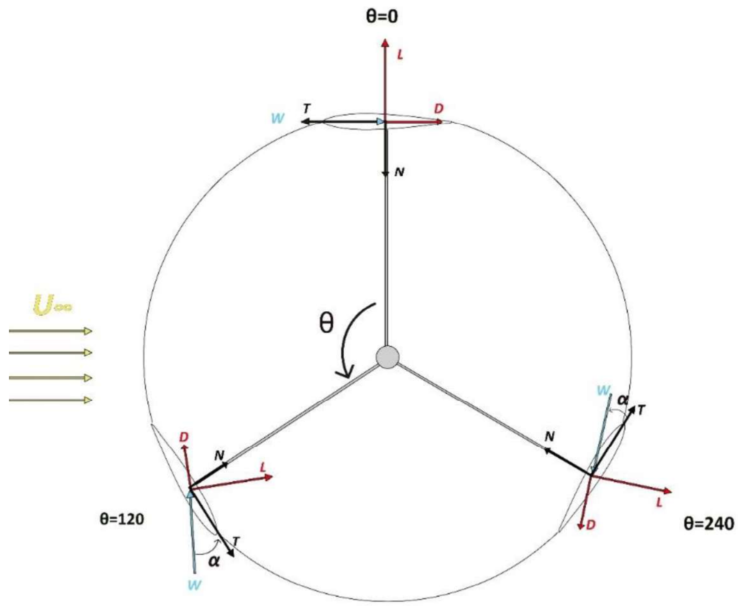

Figure 2.1 Free Body Diagram of a three-bladed vertical axis turbine rotor

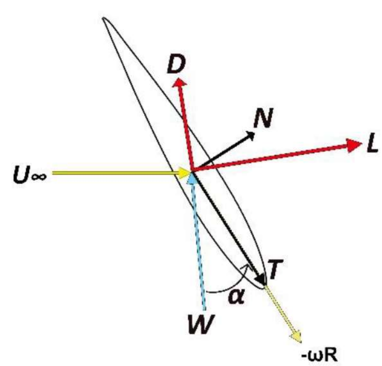

Figure 2.2 Free Body Diagram of a single turbine blade

The solidity of the turbine is illustrated in equation 2.1. The effects of tip-speed ratio are visible in equation 2.3 of angle of attack playing a significant part in the turbine's overall aerodynamics.

$$\sigma = \frac{Nc}{d} \tag{2.1}$$

$$\lambda = \frac{\omega R}{U_\infty} \tag{2.2}$$

$$\alpha = tan^{-1}[\frac{sin\,\theta}{\lambda + cos\,\theta}] \tag{2.3}$$

The resultant velocity component W in equation 2.4 can be found in relation to the tip-speed ratio and azimuthal position using the equation below.

$$W = U_\infty\sqrt{(\lambda + cos\,\theta)^2 + (sin\,\theta)^2} \tag{2.4}$$

The tangential coefficient C_T in equation 2.5 is computed from the total effective contribution of the aerodynamic coefficients resolved to the blade chord.

$$C_T = C_L\,sin\,\alpha - C_D\,cos\,\alpha \tag{2.5}$$

By using the tangential coefficient C_T, we can find the tangential force F_T using equation 2.6

$$F_T = \frac{1}{2}C_T\rho c l W^2 \tag{2.6}$$

Where *c* is the chord of the blade and *h* is the length of the blade.

The average tangential force F_{Tavg} is a function of θ and is calculated for all azimuthal positions until 2π using equation 2.7.

$$F_{Tavg} = \frac{1}{2\pi}\int_0^{2\pi} F_T(\theta)d\theta \tag{2.7}$$

Hence the average torque, τ, can be calculated as:

$$\tau = \mathrm{N}\, F_{Tavg}\, R \tag{2.8}$$

From average torque, we are able to obtain the average amount of power able to be drawn from the wind.

$$P_T = \tau\omega \qquad (2.9)$$

Using the formula for average turbine power, we can compute the coefficient of power, which is the ratio of the turbine power and power available in the wind.

$$Cp = \frac{\tau\omega}{\frac{1}{2}\rho d h V^2} \qquad (2.10)$$

Thus, from the equations explained above, we can see the relationship of the fundamental parameters of lift, drag, tip-speed ratio, azimuthal position, and angle of attack to the tangential forces that contribute to the torque and power generated by the blades. All of the above equations have been taken from Oulhaci et al., (2017) that have concluded the validity of the equations via numerical and experimental testing. Maintaining an angle of attack close to stall angle, according to these equations, create more tangential force as the ratio of C_L and C_D at most azimuthal positions would result in a higher value for C_T.

2.3 Effects of blade pitch on vertical-axis turbine performance

Blade pitch angle, β is an important parameter that serves as the basis of this research. The changing of blade pitch significantly affects the performance of the turbine, especially in variable-pitch blade. The effects of blade pitch angle on the performance of vertical axis turbine have been studied by many researchers using experimental and numerical methods, analyzing the performance in terms of coefficient of power, C_P and maximum coefficient of power, C_{Pmax}.

South & Rangi (1972), performed a wind tunnel experiment of a two-bladed Darrieus vertical axis wind turbine with a solidity of 0.07 and 2.14m radius. They reported increases in C_P of approximately 11% when their blades were offset from an initial pitch β= $-4°$ to a pitch of β= 0°, showing the effects of static pitch optimization on low solidity turbines.

Klimas & Worstell (1981), investigated the effects of blade offset on a 2.5m radius Darrieus wind turbine with a solidity of 0.22. Using a geometric analysis that relates blade pitch with equivalent preset pitch, they observed power increases of approximately 3% for blade pitch offsets of up to β= $-2°$, followed by power decreases for increasingly negative values of β. They also reported lower tip-speed ratios at C_{Pmax} for these equivalent positive pitch angles and higher tip-speed ratios for identical negative pitch angles. From their findings, we can observe the performance impact of solidity on pitch optimization too, not forgetting their analysis on different tip-speed ratio for the maximum power coefficient C_{Pmax}.

Similarly, Paraschivoiu (2002) reported on predictions of the effects of fixed pitch on the performance of a low solidity vertical axis wind turbine. His results indicate increases in predicted power of approximately 5% for a fixed-pitch of β= $-2°$, versus the zero fixed-pitch case. For all other non-zero pitch cases, rotor performance was seen to deteriorate. The observation by Paraschivoiu (2002) and Klimas & Worstell (1981) show us that solidity remains a significant influence on static pitch optimization.

Simão Ferreira & Scheurich (2014) conducted the moderate-fidelity inviscid 2D panel and 3D vorticity transport models to investigate fixed pitch angle effects. Their study investigated pitch angles of -3°,0°, and +3° and reported that although a shift in the instantaneous loads and moments was observed between the upwind and downwind sides of the turbine, the effect of pitch angle on the average loading was negligible. These findings show the importance of a higher-accuracy numerical model to predict the performance of blade pitch optimization as a whole. The effects of static pitch optimization can be low in a few cases; thus, accuracy in analyzing the impact is crucial not to denounce the effects of blade pitch as negligible.

Furthermore, the effect of fixed pitch angle was studied using high-fidelity viscous CFD simulations by Chen & Kuo (2013), Yang et al. (2018), and Sumantraa et al. (2014). However, they did not meet the performance assessments of experimental models. The effect of fixed-pitch angles -7°, -4°, -2°, -0.5°, +1° and +3° on Cp was also studied by Klimas & Worstell (1981) for a 5-m Darrieus vertical axis wind turbine in an open-field experiment where -2° was found to be the optimum although the performance gains were negligible. The study determined that a negative pitch angle provides slightly better performance.

The research on the effects of dynamic pitch optimization (or variable pitch optimization) is not as broad as static blade pitch optimization. This is mainly due to the increased complication in applying the concept in real life and the complex approach in simulations. However, Zhao et al. (2018) conducted a study on variable pitch optimization of 2 bladed H-type Darrieus turbine with a solidity of 0.09 at a tip-speed ratio of 4.5. They concluded an 18.9% increase in peak power efficiency and predicted the model's viability for different tip-speed ratios, indicating that the variable or dynamic pitch approach gives the most favourable outcome.

Abbaszadeh et al. (2019) carried out a similar pitch optimization technique in a closed-loop hydraulic channel in the LEGI Laboratories, Grenoble. However, due to the lower tip-speed ratio nature of hydrokinetic turbines, they could increase power by 122% for a dynamically pitched turbine than an unpitched turbine. These findings show the significance of tip-speed ratio on dynamic pitch optimization. Thus, further research should be conducted to improve further the dynamic pitch optimization model/method of a vertical axis turbine to rival a horizontal axis turbine's efficiency and performance advantage.

2.4 Background on Qblade

Qblade is an open-source framework developed to simulate and design wind turbines in horizontal and vertical orientations. The software will be used extensively in analyzing the dynamics and performance of the vertical axis blade, inclusive of variable-pitch blade. The Blade Element Momentum (BEM) method is utilized in Qblade for the simulation of horizontal axis turbine, and a Double Multiple Streamtube (DMS) algorithm together with a Lifting Line Theory Free Vortex Wake (LLT) method are used to simulate vertical axis turbine performance (D Marten & Wendler, 2013).

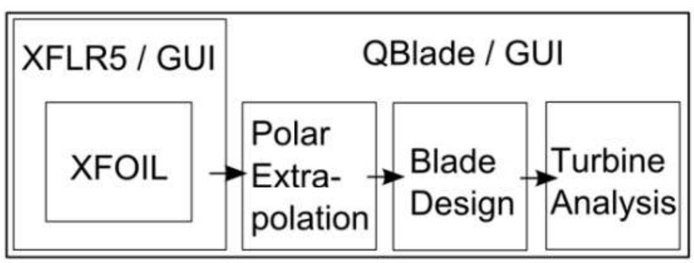

Figure 2.3 Software Modules in Qblade

The algorithms used to simulate the turbine performance require an initial lift and drag coefficients dataset at various angles of attacks. These data are obtained via experiments or through two-dimensional airfoil simulations from XFOIL. The software developed at the Massachusetts Institute of Technology analyzes and computes the flow around airfoils at a subsonic level. XFOIL combines a high-order panel method with a fully coupled viscous/inviscid interaction method (Drela, 1989).

The XFOIL algorithm is limited in predicting lift and drag coefficients at various angles of attacks just before and after stall angle since it is only based on potential flow theory. Application for very high or low angle of attacks is not achievable or does not converge by using its algorithm.

2.4.1 360° Airfoil Polar Extrapolation

The polar data from XFOIL are only generated up to a specific range of angle of attack, that is just right after stall. Thus, XFOIL generated airfoil polars need to be extrapolated to the whole 360° angle of attack to ensure the smooth operation of the DMS and LLT simulation of vertical axis turbines. A typical procedure to extrapolate the airfoil polars is to apply curve fits to the stalled polar curves. In such cases, the airfoil is assumed to be a thin plate at a high angle of attack with a sharp leading edge. Qblade has two extrapolation methods, the Viterna-Corrigan post-stall model (or more generally known as the Viterna extrapolation model) and the more recently developed Montgomerie extrapolation model (Mahmuddin et al., 2017).

2.4.2 Blade Design

The next step in simulating a vertical axis turbine is by designing the blades to be used in the turbine. Qblade's blade designer module offers an efficient and intuitive design of rotors and blade shapes. A CAD model in the form of a .stl format is implemented to visualize the blade. A general method in designing a vertical axis turbine blade is by distributing a series of airfoils (usually of similar profile) created in the airfoil module over various blade sections. The blade designer would then further allow for any specific shapes in twisting or curling the blade to design a helical or unique turbine shape. The geometry is further defined by specifying chord length, the radius of the rotor, azimuthal angle, and the length of the blade. Figure 2.4 shows a snapshot of the graphical user interface of Qblades blade designer. The OpenGL render of the blade also helps the user to observe the blade design in the process visually.

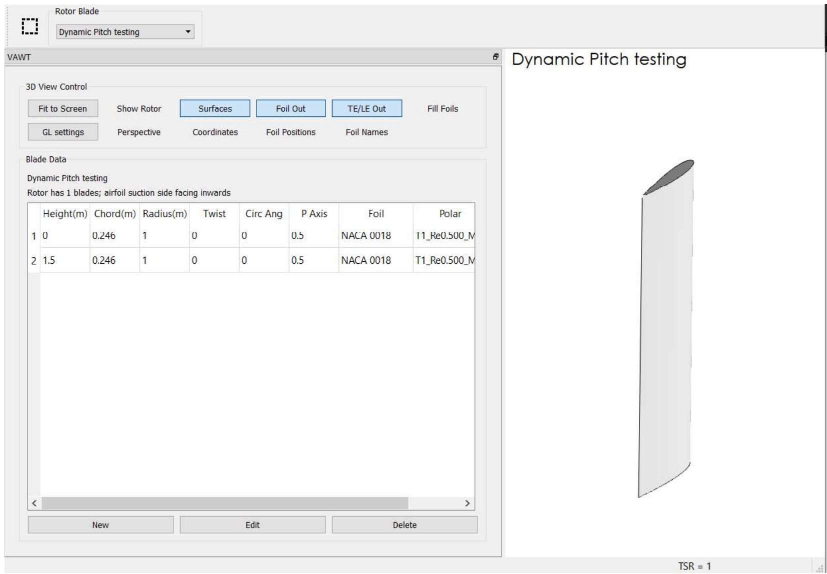

Figure 2.4 The Blade Designer module in Qblade

2.4.3 Turbine Analysis

In the wind turbine industry, methods based on blade element theory with a momentum balance over single or multiple streamtubes are commonly used. These methods are used for testing performance for rapid development, and a comparison of different rotor designs is possible. The lower fidelity and accuracy of the methods can be an excellent preliminary wind turbine design that can be expanded using the means of CFD techniques. Verifying the computational efficiency of methods used by Qblade with pre-existing wind turbine data and high-fidelity simulations validates the application to analyze rotor blades from a preliminary standpoint.

2.4.4 Double Multiple Streamtube Model

Paraschivoiu (2002) developed the DMS algorithm used in Qblade's aerodynamic module for vertical axis wind turbine. Similar to BEM methods, the DMS algorithm combines the blade forces inclusive of a momentum balance. Because the vertical axis wind turbine experiences airflow in the upwind and downwind region once each for one revolution, it can be idealized into two horizontal axis wind turbines placed in a row. The circumferential angle, relative velocity, and the instantaneous position of the blades affect the instantaneous angle of attack of the rotor blade.

The DMS method does not come without drawbacks; dynamic stall effects and empirical corrections for the aerodynamic influence of the struts and other rotor parts have to be considered separately. A more sophisticated DMS model would take into account the streamtube expansion. However, in the current version, Qblade only compensates for tip losses, finite aspect ratio, and optional interference factors. Figure 2.5 shows the graphical user interface of the DMST module in Qblade to simulate multiple parameters at once.

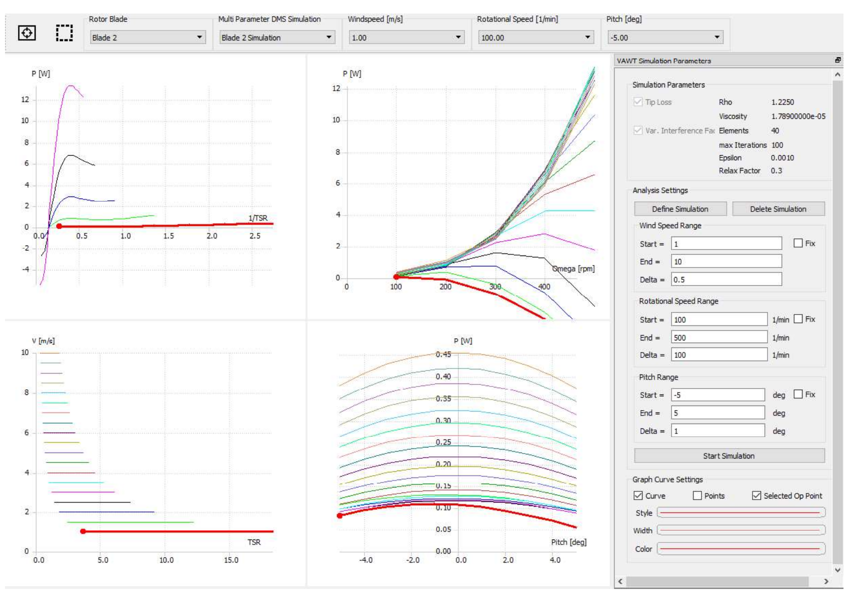

Figure 2.5 DMST module interface in Qblade

2.4.5 Non-Linear Lifting Line Thoery

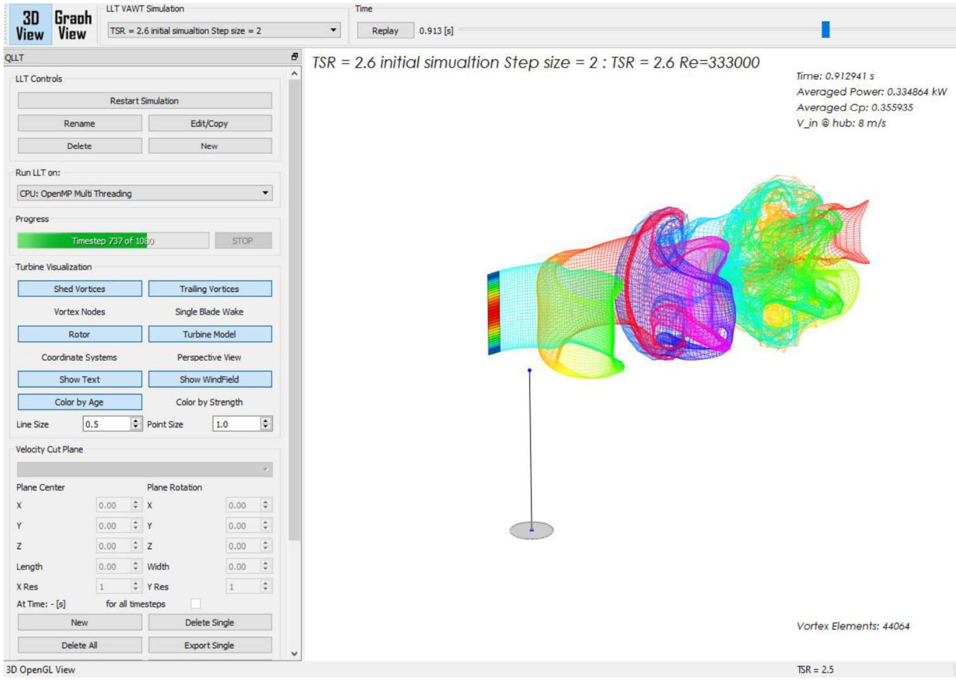

Figure 2.6 The LLT module interface in Qblade

The lifting line free vortex wake (LLT) algorithm in Qblade is a general simulation method used to model vertical axis and horizontal axis rotors with an acceptable degree of accuracy. The forces acting on the blade are calculated using the lifting line theory formulation. The distributed vortices are used to model the circulation of flow located at the quarter chord position of the blade. The circulation is computed by using pre-existing airfoil polar data from experiments or two-dimensional numerical simulations of blade inflow angle calculated under the influence of the free wake induction. The wake is explained as freely floating vortex elements shed from the trailing edge for every azimuthal or time step. In contrast to the BEM method, this simulation method is more accurate and reliable with fewer assumptions.