INVESTIGATION ON DYNAMICS, PERFORMANCE AND PITCH ANGLE OPTIMIZATION OF VERTICAL-AXIS TURBINES

by

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ENDORSEMENT

I, Lim Yew Hao hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly

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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.

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INVESTIGATION ON DYNAMICS, PERFORMANCE AND PITCH ANGLE OPTIMIZATION OF VERTICAL-AXIS TURBINE

ABSTRACT

To meet increasing global demand for energy, renewable energy sources are endorsed as a solution for the energy crisis. Hydrokinetic energy, the eco-friendly alternative for traditional hydropower that extract kinetic energy from water flow through hydrokinetic turbines has potential to be the replacement for the depleting fossil fuels. Vertical-axis hydrokinetic turbine, with its scalability and omnidirectional characteristic, is a fitting renewable energy supply for off-grid rural areas. However, the existing issue of low performance efficiency hinders the large-scale application of vertical-axis turbine. It is suggested that applying pitch angle to turbine blade is a simple modification that can improve the low performance efficiency of the vertical-axis turbine. This research aims to investigate the effects of pitch angle to vertical-axis turbine dynamics and power performance through numerical simulation. The problems associated with this research are the effects of pitch angle on turbine performance and the optimum pitch design for different operating conditions. Pitch angle effects would be investigated through analyses of simulation results in terms of instantaneous aerodynamic loadings and average power coefficient. Pitch angle optimizations are then performed on the same turbine model to determine optimum pitch angles that maximize turbine performance at different tip speed ratio. To conduct the investigation, a numerical simulation model of a Darrieus type straight-bladed vertical-axis turbine with 3 blades is completed using MATLAB with

incorporation of NACA 0021 airfoil data. Blade Element Theory and various assumptions that represent physical turbine operating conditions are applied to create turbine simulation that can adequately predict turbine performance. Validation studies are then conducted by comparing the simulated results with computational fluid dynamics simulation and experimental data, to ensure that the simulation results are accurate and reliable. It is found that, the simulation model is able to simulate results with less than 10% of error at low tip speed ratio. Fixed-pitch angle and dynamic-pitch angle optimizations are then carried out by modifying the numerical model to determine optimum pitch angles. With the simulation results, the effects of pitch angle on the instantaneous angle of attack, tangential force coefficient, normal force coefficient, and power coefficient are analyzed. It is found that fixed-pitch optimization improves on turbine performance efficiency by reducing drag-induced tangential force component in the downstream region. Fixed pitch optimization is able to increase turbine power coefficient by 5.24% at the tip speed ratio of 1. Dynamic-pitch optimization, however, increases turbine power coefficients by maximizing the lift-induced tangential force component while minimizing drag-induced component. Dynamic-pitch optimized turbine model produces power coefficient that improves for 626.92 % compared to zero-pitch turbine model. Due to the limitations and assumptions made, the simulation model is suitable to be applied in fundamental understanding and preliminary design of vertical-axis turbine.

PENYELIDIKAN TENTANG DINAMIKA, PRESTASI DAN OPTIMISASI SUDUT LARAS ATAS TURBIN PAKSI MENEGAK

ABSTRAK

Untuk memenuhi keperluan global yang semakin meningkat untuk tenaga, sumber tenaga boleh diperbaharui dianggap sebagai penyelesaian untuk krisis tenaga ini. Tenaga hidrokinetik, alternatif mesra alam kepada tenaga hidroelektrik tradisional, mengeluarkan tenaga kinetik daripada aliran air melalui turbin hidrokinetik, berpotensi untuk dijadikan pengganti kepada bahan bakar fosil. Turbin hidrokinetik paksi menegak, dengan sifat skalabilitas dan sifat kepelbagaian arahnya, adalah bekalan tenaga boleh diperbaharui yang sesuai untuk kawasan luar bandar yang tidak bersambung dengan grid elektrik. Walau bagaimanapun, masalah kecekapan prestasi rendah yang sedia ada menghalangi aplikasi turbin paksi menegak berskala besar. Aplikasi sudut laras ke atas bilah turbin telah dicadangkan sebagai pengubahsuaian mudah yang dapat meningkatkan kecekapan prestasi turbin paksi menegak. Penyelidikan ini bertujuan untuk mengkaji kesan sudut laras kepada dinamik dan prestasi kuasa turbin paksi menegak melalui simulasi berangka. Persoalan yang dikaitkan dengan penyelidikan ini adalah kesan sudut laras kepada prestasi turbin dan reka bentuk padang optimum bagi keadaan operasi yang berbeza. Kesan sudut laras akan diselidiki melalui analisis keputusan simulasi dari segi beban aerodinamik seketika dan koefisien kuasa purata. Kemudian, pengoptimuman sudut laras dijalankan pada model turbin yang sama untuk menentukan sudut laras optimum yang memaksimumkan prestasi turbin pada nisbah kelajuan hujung yang

berbeza. Untuk menjalankan siasatan ini, model simulasi berangka turbin paksi menegak Darrieus dengan 3 bilah telah dibinakan melalaui penggunaan MATLAB dengan data aerofoil NACA 0021. Teori Unsuran Bilah dan pelbagai anggapan yang mewakili keadaan operasi fisikal yang dialami oleh turbin telah digunakan untuk menwujudkan simulasi turbin yang dapat meramalkan prestasi turbin. Kemudiannya, kajian pengesahan telah dijalankan melalui pembandingan hasil simulasi dengan simulasi pengiraan dinamik bendalir dan data eksperimen, untuk memastikan keputusan simulasi adalah tepat dan boleh dipercayai. Keputusan kajian pengesahan mendapati bahawa model simulasi dapat mensimulasikan keputusan dengan kesilapan yang kurang daripada 10% pada nisbah kelajuan hujung yang rendah. Seterusnya, pengoptimuman sudut laras tetap dan dinamik telah dilakukan dengan mengubah model berangka untuk menentukan sudut laras optimum. Dengan keputusan simulasi, kesan sudut laras kepada sudut serangan, koefisien daya tangen, koefisien daya normal, dan koefisien kuasa dapat dianalisiskan. Keputusan menunjukkan pengoptimuman sudut laras tetap dapat meningkatkan kecekapan prestasi turbin dengan mengurangkan komponen koefisien kekuatan tangen yang disebabkan oleh daya seret. Pengoptimum sudut laras tetap dapat meningkatkan koefisien kuasa turbin sebanyak 5.24% apabila nisbah kelajuan tip adalah 1. Pengoptimuman sudut laras dinamik, dapat meningkatkan koefisien kuasa turbin dengan memaksimumkan komponen daya tangen yang disebabkan oleh daya angkat sementara meminimumkan komponen daya seret. Model turbin dengan aplikasi Pengoptimuman sudut laras dinamik dapat menghasilkan koefisien kuasa yang meningkat sebanyak 626.92% berbanding dengan model turbin yang tidak bersudut laras. Disebabkan oleh batasan dan anggapan yang termasuk dalam model turbin berangka, model simulasi ini adalah sesuai untuk diaplikasikan dalam pemahaman asas dan reka bentuk peraingkat awal untuk turbin paksi menegak.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AOA	:	Angle of attack
CFD	:	Computational Fluid Dynamics
VAT	:	Vertical-axis turbine
TSR	:	Tip speed ratio

LIST OF SYMBOLS

C_P	:	Power coefficient
β	:	Pitch angle $[deg]$
θ	:	Azimuthal position $[deg]$
R	:	Rotor Radius $[m]$
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 $[kg/m^3]$
μ	:	Flow Dynamic viscosity $[kg/ms^{-1}]$
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_{t_L} : Lift component of tangential force coefficient

C_{t_D} : Drag component of tangential force coefficient

C_n : Normal force coefficient

C_{n_L} : Lift component of normal force coefficient

C_{n_D} : Drag component of normal force coefficient

C_Q : Torque coefficient

V_b : Turbine blade rotational velocity $[ms^{-1}]$

ω : Turbine blade angular velocity $[rad\ s^{-1}]$

V_t : Turbine blade tangential velocity component $[ms^{-1}]$

V_n : Turbine blade normal velocity component $[ms^{-1}]$

V_a : Upstream flow induced velocity $[ms^{-1}]$

$V_a{}'$: Downstream flow induced velocity $[ms^{-1}]$

V_r : Blade relative flow velocity $[ms^{-1}]$

F_t : Tangential force $[N]$

F_n : Normal force $[N]$

F_{ta} : Average tangential force $[N]$

Q : Torque $[Nm]$

P : Power output $[W]$

A	:	Rotor swept area $[m^2]$
V_e	:	Flow velocity at equilibrium $[m^2]$
a	:	Upstream flow interference factor
a'	:	Downstream flow interference factor

CHAPTER 1
INTRODUCTION

1.1. Motivation

Escalating global energy demand, which is estimated to grow for almost 50% from 2010 to 2030 (Behrouzi et al., 2016), indicates the possibility of an energy crisis. Coal, oil, and natural gas, which account for 80% of the source of energy, are rapidly depleting. Over-reliance on fossil fuels is unsustainable as well as ecologically destructive, causing global warming and greenhouse effect. It is observed that for every kilowatt-hour (kWh) of electricity generated with coal, 1689 grams of carbon dioxide equivalent greenhouse gases emission is produced (Salleh et al., 2018). Exposure of the particles emitted from the combustion of fossil fuel affects human health negatively. Long-term exposure to such pollutions can even lead to fatal diseases including lung cancer, stroke, and cardiovascular diseases.

As a solution to the elevating energy demand and pollution level, new energy sources must be explored and utilized to replace the traditional sources. However, in majority of the developing countries, electricity is generated by power stations that use fossil fuels as sources because of low operation and maintenance costs (Chong et al., 2013). Despite the lower costs of such power stations, unsustainability and pollution factors do call for more sustainable and eco-friendly alternatives. As such, the utilization of renewable energy sources is endorsed as substitutes of fossil fuels, to meet the world increasing demand for electricity with minimal environmental impact.

In Malaysia, hydropower is the only type of renewable energy source that has nationwide, large-scale application. Currently, hydropower accounts for 8.7% of Malaysia's total electricity generation while fossil fuel still is the dominant energy source with more than 80% of the total electricity generation (Salleh et al., 2018). To promote renewable energy growth and applications, Malaysia government launched The Renewable Energy Act 2011, which focused on renewable energy in electricity generation. Hydropower has the potential 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 limited or no accessibility to power grid linked to large scale power stations or hydropower plants due to their remote geographical locations and small population sizes. The limited amount of electricity usage is unable to justify the costs involved in connecting those areas to large scale power grid. With limited options, the residents of those areas have no choice but to rely on the out-of-date diesel or gasoline generators for their electricity supply. These generators produce byproducts of air pollutants and noise emission that are detrimental to the people and environment around them.

In remote areas, where building power stations is not plausible, vertical-axis hydrokinetic turbine can be the fitting solution for renewable energy supply. Malaysia with its vast and dense networks of rivers and streams, has potential in power generation using hydrokinetic vertical-axis turbine. Kinetic energy of water current can be captured through hydrokinetic turbine with minimal environmental effect. Vertical-axis hydrokinetic turbines' scalability and omnidirectional characteristics enable applications with different sizes and scales depending on the size of water sources regardless of current flow patterns.

However, existing issues of low performance efficiency and energy-to-cost ratio prevent the potential of hydrokinetic vertical-axis turbine application to be fully realized. When water passes through a horizontal-axis turbine, all turbine blades contribute to energy production. When water passes through a vertical-axis turbine, only a fraction of its blades generates positive torque that promotes energy production. Consequently, researchers develop and explore extra design details and optimization to improve vertical-axis turbine performance efficiency.

In this research project, the performance of vertical-axis turbine is studied through semi-empirical low order numerical simulation using MATLAB. Due to the assumptions made and limited computer processing power, low order simulation cannot compete with experimental approach or high order simulation approach including CFD simulation in terms of result accuracy. However, its low computer processing power and time requirements allow more flexible simulation. Investigation and simulation of turbine performance in larger range of input parameters and operating conditions can be carried out without spending large amount of cost and time for computational or experimental setup.

1.2. Overview

Conventional hydropower technology extracts potential energy from water sources with artificial head differences. The artificial water-head is created through the building of dams and water storage. Dams and water barriers constructions alter the natural pathway of the water flow and create a negative impact on the environment. Natural habitats of wildlife are lost due to the need for extensive land for the constructions, making the traditional hydro technology unsustainable.

As a solution to the unsustainability of the traditional hydropower concept, the concept of hydrokinetic energy emerges. Hydrokinetic power generation exploits the kinetic energy from the natural flowing water rather than artificially creating head differences. As this concept does not involve major changes to the environment, its environmental impact is minimal compared to the traditional approach. There is an abundance of natural or artificial flowing water sources around the globe that are yet to be utilized to generate hydro energy. Waves, tides, ocean currents, river currents, as well as man-made channels and industrial outflows, hold kinetic energy that can be converted to electricity. Hydrokinetic turbine is the prime system for such kinetic energy to electricity conversion (Gauntlett et al., 2009).

The types of hydrokinetic turbine can be characterized according to the rotational axis orientation relative to water flow direction. The two main types of hydrokinetic turbine are horizontal-axis/axial turbine and vertical-axis turbine (Güney et al., 2010). Vertical-axis turbines can be classified into two types: Darrieus turbines (lift-type turbines) and Savonius turbines (drag-type turbines). Darrieus turbines that operate on lift force operates at a higher relative speed, produce more power compared to Savonius turbines. Darrieus turbine can be further classified by their blade design: straight-bladed (Squirrel cage or H-type Darrieus) and curved bladed turbines.

Axial turbines have been successfully implemented in large-scale applications because of their advantages of high performance efficiency. The blades are designed to be tapered and twisted in a way that lift force is exerted evenly along the blades. Such design also ensures that axial turbines are capable of self-starting without external mechanism. Furthermore, axial turbines also have a larger knowledge base with more large-scale applications, researches, and literature on system design and performance (Khan et al., 2009).

Vertical-axis turbines, on the other hand, have several advantages over axial turbines: they are omnidirectional which means they can harness energy from water current flowing in any direction, therefore they do not need additional yawing mechanisms unlike axial turbines (Asr et al., 2016). Also, they operate with lower noise emission because of slower operating current speed. Vertical-axis turbines are relatively simple in their design, thus, require lower manufacturing, maintenance, and installation costs (Davood et al.,2013). Low design complexity enables vertical-axis turbines to be more scalable than axial turbines. Despite their advantages, most applications of vertical-axis turbines are still in small-scale, research state because of their limitations of low performance efficiency and low starting torque that compromises self-starting capability (Bianchini et al., 2015; Kirke et al., 2011).

Identical to a wind turbine, kinetic energy from flowing water sources is captured by hydrokinetic vertical-axis turbine in the form of mechanical power that rotates a generator to produce electricity. Interactions of water current with blade generates aerodynamic lift and drag forces, the aerodynamic forces contribute to blade tangential force which subsequently generates torque. The torque generated in the positive direction will then induces the turbine rotor rotation that leads to power generation.

Drawbacks associated with vertical-axis turbines prevent their large-scale commercialization despite the advantages (Hu et al., 2012). To address the drawbacks, modifications on the rotor, blade design, and additional mechanism including duct augmentation are proposed and their effects on turbine performance enhancement are investigated. It is found that fixed blade pitch angle optimization is a relatively simple way to improve turbine efficiency or self-starting capability (Rezaeiha et al., 2017).

1.3. Problem Statement

Blade pitch angles affect turbine loading experienced by vertical-axis turbine, thus changes the average torque generated and the overall turbine efficiency. The effects of pitch angle are dependent on the flow condition experienced by turbine blade. For vertical-axis turbine, its blades experience different loading and flow conditions throughout a revolution. The question then arises as to how does pitching affects aerodynamics and flow physics of the turbine at different azimuthal position?

Variation of blade pitch angles produces different effects on turbine loading, average torque and power coefficient. Optimal pitch angle is the pitch angle that enables maximum turbine performance. Consequently, applying optimum pitch angle on vertical-axis turbine seems to be a viable solution to the issue of low performance efficiency. However, the optimum pitch angle for vertical-axis turbine varies with turbine design and operating condition. The same pitch angle is capable of improving or deteriorating turbine performance under different operating condition. This raises the question of how what is the optimum pitch angle under different operating condition and turbine design?

1.4. Objectives

To address the problems described above, this research project aims to attain the objectives:

- To create a numerical program that can predict the turbine efficiency and effects of pitch angle to performance of vertical-axis turbine.
- To carry out optimization on turbine blade pitch angle to maximize vertical-axis turbine performance efficiency under different operating conditions.

1.4.1. Numerical Turbine Model

To study and analyze the effects of blade pitch angle to vertical-axis turbine, a turbine model that can predict performance of turbine in specific condition accurately, is essential. Equations, parameters, and assumptions are applied with design specifications and operating conditions to complete the numerical program. The finished program should be able to determine output performance parameters of vertical-axis turbine when operating condition, turbine design, and turbine blade pitch angle inputs are specified.

1.4.2. Turbine Blade Pitch Angle Optimization

The effects of pitch angles to turbine performance are analyzed by running different pitch angles as inputs for the numerical program. The optimization process on blade pitch angle will then be carried out by selecting the pitch angle input that enables turbine to maximize its performance. Both fixed-pitch and dynamic pitch optimization are performed based on the output performance parameters of the numerical program. The optimal pitch design for maximum turbine performance at different conditions will be determined.

1.5. Research Scope

The scope of the research is limited to semi-empirical investigation which is a combination of numerical approaches and experimental data. Numerical turbine model is created to simulate and predict turbine performance in terms of performance parameters. However, fluid flow pattern and fluid dynamics of the flow through turbine blades are not modeled. Alternatively, experimental airfoil data is imported and utilized as lift and drag coefficient data. The experimental airfoil data are then applied as input parameters for the numerical simulation.

The configuration of the vertical-axis turbine is limited to lift-based Darrieus H-type turbine with straight-bladed design. Airfoils are selected as blade profile of the turbine depending on availability of the airfoil lift and drag coefficient data which are necessary to complete the simulation. The scale, size, radius, number of blades, and other design specifications of the turbine are described in the Methodology chapter.

This research focuses on investigating the effect of blade pitch angles to performance efficiency of vertical-axis turbine. The optimum blade pitch angle which maximizes turbine efficiency under specific operating condition is the desired outcome of this research. Research suggests that applying pitch angle to turbine blade can improve turbine performance efficiency without elevating design complexity and fabrication cost (Bianchini et al., 2015). The optimization of blade pitch angle will be conducted in 2 approaches. The first being fixed-pitch optimization approach that set a constant pitch angle for a complete revolution. The second approach, dynamic-pitch optimization which involved higher design complexity, identifies optimum pitch angle at each azimuthal position throughout a revolution.

In the real situation, vertical-axis turbine will accelerate be accelerated by fluid flow kinetic energy starting from the static condition until it reaches terminal rotational velocity where the fluid flow could no longer accelerate the flow. However, for this research, angular acceleration is neglected, and the vertical-axis turbine is assumed to be rotating at a constant velocity defined by tip speed ratio input.

In actual operation, the heavier turbine would require higher kinetic energy and longer time to accelerate to the same rotational velocity when compared to lighter turbines due to the larger moment of inertia. Similar to the angular acceleration, effect of mass and moment of inertia of vertical-axis turbine are neglected in this research.

Flow pattern relative to turbine blade varies as turbine rotates and operating condition changes. Modelling of the actual flow pattern would add to the complexity and difficulty of the numerical model. Consequently, flow relative to turbine blade is assumed to be in a linear pattern. Details of assumptions made to the numerical turbine model are discussed in depth in the Methodology chapter.

1.6. Thesis Layout

The outline of the thesis is as follows: Chapter 2, Literature Review, presents the review on literature about turbine performance simulations, recent modifications on vertical-axis turbine, investigation and optimization of turbine blade pitch angle. Simplified turbine model, theories, equations, and assumptions applied in the numerical model, programming approach, optimization approach, and validations on the numerical turbine model are presented in Chapter 3, Methodology. Chapter 4, Results and Discussions, displays and analyses result of Baseline model, fixed-pitch optimization, and dynamic-pitch optimization; discusses pitch effect to turbine performance, optimum pitch angle at various operating conditions, evaluation of the feasibility of results and effect of induced flow. Conclusions and recommendations are presented in Chapter 5, Conclusions and Recommendations.

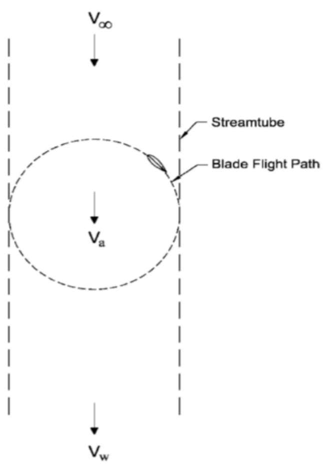
CHAPTER 2

LITERATURE REVIEW

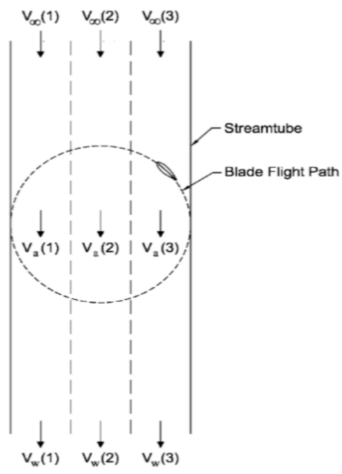
2.1. Vertical-axis Turbine Numerical Simulations

The key in the development of performance prediction and optimization model of a vertical-axis turbine is to have a clear understanding of turbine operation and flow behavior. Simulation tools in the form of numerical model are created to understand and predict the performance of vertical-axis turbines under different conditions.

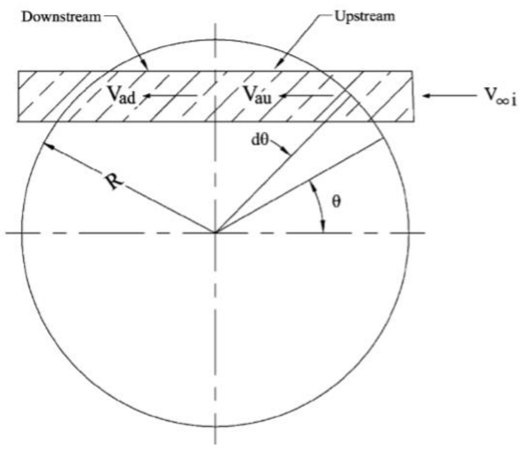
Islam et al. reviewed and discussed the feasibility of some of the most widely applied aerodynamic models developed to predict vertical-axis turbine performance (Islam et al. 2008). The models include: streamtube momentum models, the Vortex model and the Cascade model. The schematic of the aerodynamic models is shown in Figure 2.1. It is found that streamtube models, including single and double multiple streamtube models, can predict turbine performance with reasonable accuracy with limited computational power and cost. However, the streamtube models are not suitable for high tip speed ratio applications and high solidity vertical-axis turbine. Vortex model is a potential flow model that calculates velocity around the turbine based on Prandtl's Lifting Line Theory. It has the highest accuracy but requires high computational cost. The Cascade model assumes that turbine blades are positioned on plane surface with equal distance. Islam et al. also suggest that the Cascade model can be used to predict high solidity vertical-axis turbine performance at high tip speed ratio with adequate accuracy.



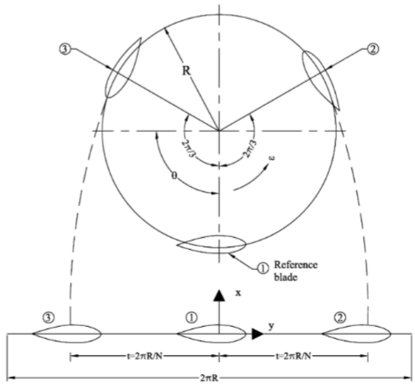
(a) Single streamtube model



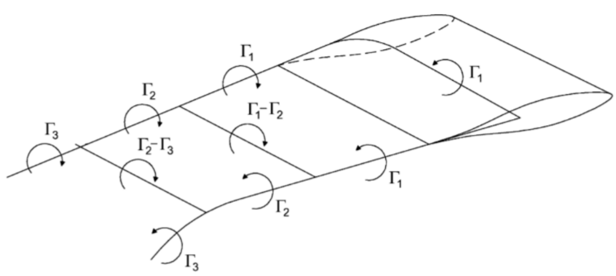
(b) Multiple streamtube model



(c) Double multiple streamtube model



(d) Cascade model



(e) Vortex Model

Figure 2.1: Schematic of aerodynamics models (Islam et al. 2008)

Ferreira et al. (2014) compared and discussed the difference for 6 different aerodynamic model for investigation on effect of changing pitch angle to thrust and power coefficient of vertical-axis turbine. It is found that multiple streamtube model and double multiple streamtube models produce results that deviate significantly from other aerodynamic models. Nonetheless, they suggest that the multiple streamtube models can still be a viable numerical simulation tool if empirically corrected. The other models include Actuator Cylinder model, a two-dimensional (2D) potential flow model (U2DiVA), a three-dimensional (3D) unsteady lifting line model (CACTUS code), and a 2D conformal mapping unsteady vortex model (ARDEMA 2D). These models include the modelling of wake as part of the numerical model, thus are able to produce similar results that are consistent with the theory of changing pitch angle. Despite the positive results, Ferreira et al. deduced that the level of uncertainty for the numerical models is still too high for design purposes.

2.2. Computational Fluid Dynamics Simulations

In recent years, detailed analyses of vertical-axis turbine performance have been performed using Computational Fluid Dynamics (CFD) tools that improve on results accuracy compared to numerical modelling. CFD analyses eliminate assumptions required for numerical model to represent three-dimensional, turbulent flow dynamics and enable a better understanding of time-dependent flow field and wake effect. However, the improved accuracy does require much greater computational cost and much refined parametric analysis. Rezaeiha et al. (2017b) carry out 2-Dimensional and 2.5-Dimensional CFD simulations to predict vertical-axis turbine performance in terms of power coefficient, C_P and velocity components. The CFD simulations are done with Unsteady-Reynolds-Averaged Navier-Stokes (URANS) using ANSYS Fluent software. Both 2D and 2.5D CFD simulations have good agreement with experimental data of the same turbine model. Both 2D and 2.5D CFD simulations have a difference of 2.5% in C_P compared to the experimental result. In terms of velocity components, normalize lateral velocity between CFD simulations and experimental data has an average deviation of less than 3% while normalize streamwise velocity has an average deviation between 8 to 16%. The results show that both 2D and 2.5D CFD simulations are capable of predicting vertical-axis turbine performance at very high accuracy, proving that CFD simulation is suitable to be applied in detailed turbine modelling.

2.3. Semi-empirical Approaches

Semi-empirical approach to turbine performance simulation is the combination of experimental data application and numerical simulation. Addition of experimental data improves on the simulation accuracy of simplified numerical turbine model. Elhadji et al. (2015) assessed the difference between CFD and semi-empirical approaches on vertical-axis turbine performance analysis. In semi-empirical approach, experimental data from Angstrom Lab Vertical-axis group in Uppsala University are applied to the existing double multiple streamtube model. For CFD approach, 2D CFD simulation on the same turbine model is carried out using ANSYS Fluent. It is found that results from semi-empirical approach behaves in a similar trend with CFD results, however, there is a significant phase lag between the two results. Bah et al. conclude that the semi-empirical approach is an improvement over numerical model and it is well suited for better understanding of vertical-axis turbine operation and screening of turbine designs. CFD tools, on the other hand, are suitable for detailed modelling and design refinement.

2.4. Recent Vertical-axis Turbine Modifications

Several solutions and designs have been proposed to increase efficiency and self-starting ability of vertical-axis turbine. Duct augmentation was applied to increase the current speed and Reynold's number where the turbine operates in, to increase total power generated, thus improve turbine efficiency (Ponta et al., 2000). Duct augmentation involves the installation of ducting channels that induce sub-atmospheric pressure within a constrained area, thus increases local flow velocity. This approach does successfully improve turbine efficiency; however, the installation of external ducting channels adds to the manufacturing, installation, and maintenance costs of operating a vertical-axis turbine. So, the power generated to cost ratio is reduced, making this an ineffective solution.

For more reliable self-starting performance for vertical-axis turbines, form-changing turbine blade was introduced to increase drag properties at low tip speed ratio to increase starting torque (Bhatta et al., 2008). This approach is a viable solution to improve self-starting ability of vertical-axis turbine especially with the advancement in manufacturing technology that will lower down the manufacturing costs and difficulties significantly. Similarly, new blade profiles and blades with opening trailing edges are introduced to solve the same problem of unreliable self-starting ability (Douak et al., 2015). Guide vanes and external self-starting mechanism are applied in some cases in response to the self-starting reliability issue for vertical axis turbine (Shahizare et al., 2016). However, they do have drawbacks in terms of cost-effectiveness and design complexity.

Generally, recent solutions to the issues possessed by vertical axis turbine serve their specific purposes but with drawbacks and unwanted byproducts including increased design complexity and higher fabrication, maintenance and installation costs.

2.5. Pitch Effect and Optimization

Applying pitch angles to turbine blade is a modification that can be done to vertical-axis turbine to alter its performance efficiency without elevating its design complexity and fabrication costs. The effect of the fixed pitch angles on power coefficient, C_P was studied for a high-solidity H-type VAT in an open jet wind tunnel (Fiedler et al., 2009). Blade pitch angles, β of -7.8°, -3.9°, +3.9°, and +7.8° are applied to the vertical-axis turbine. The study concluded that a negative pitch angle is able to enhance turbine performance in the form of increased C_P. Blade pitch angle, β of -3.9° produce a 20% gain in maximum C_P.

Rezaeiha et al. (2017a) investigated the effect of applying fixed pitch angle to aerodynamics and power performance of vertical-axis turbine through CFD simulation. In their investigation, pitch angle ranges from -7° to +3° are applied to straight-bladed Darrieus type turbine. It is found that pitch angles affect instantaneous and average loading on turbine blades, instantaneous moment acting on turbine blades shift between upstream and downstream halves of turbine rotation. Besides, pitch angle changes the strength of vortices and wake generated by turbine blades. The result shows that the turbine reaches its maximum C_P at the tip speed ratio of 4 when β of -2° is applied. The maximum C_P has an increment of 6.6% compared to the same turbine model with zero pitch angle. Rezaeiha et al. also suggest that dynamic pitching might be a viable way for further performance optimization.

Yang et al. studied the effect of fixed pitch angle on straight-bladed vertical-axis turbine through wind tunnel experiment and CFD simulation (Yang et al., 2018). The effect of pitch angle on pressure distribution, torque and power coefficient are the focus of the study. Their result shows that torque coefficient acting on a single blade is maximum at β of 6°. At tip speed ratio of 2.19, C_P of turbine reaches its maximum value at β of 6°. Yang et al. conclude that, when compared to horizontal-axis turbine, blade pitch angle is less effective to vertical-axis turbine in terms of its effects on aerodynamics and power coefficient.

To determine the optimum pitch angle to be applied on vertical-axis turbine to achieve its maximum performance, pitch optimization is implemented by Bianchini et al. on small size vertical-axis turbine (Bianchini et al., 2015). The optimization process is implemented on a numerical model that applies blade element momentum theory. Turbine power output is the dependent variable of the optimization process. It is found that pitch angle induces a change in torque intensity and distribution pattern. They concluded that optimal pitch angles which are below 3° are able to produce an increase in turbine power output.

Though dynamic pitching on turbine blades might increase its design complexity and fabrication cost, it is still considered as a promising idea to increase vertical-axis turbine performance efficiency to a point where large-scale application is feasible. Jain et al. predicted and analyze the performance of vertical-axis turbine with variable amplitude dynamic blade pitching (Jain et al., 2016). The analysis is completed via numerical simulation with double multiple streamtube model. From the simulation result, they conclude that applying dynamic pitch allows the turbine to reach its maximum power output at a wide range of tip speed ratios. At tip speed ratio of 1 to 2.5, peak C_P that is larger than 0.3 can be achieved with dynamic pitch amplitude of 8° to 30°. However, at tip speed ratio lower than 0.5, higher pitch amplitude which is about 35° is required to increase turbine performance.

CHAPTER 3

METHODOLOGY

This chapter presents the simplified turbine model developed and used to carry out numerical simulation of vertical-axis turbine performance. The theories and assumptions behind the numerical model, the programming approaches, the optimization strategies and validation studies of the model are described in this chapter.

3.1. Simplified Turbine Model

For the current investigation a straight-bladed (H-type) Darrieus vertical-axis turbine is applied in the creation of a simplified vertical-axis turbine model. The turbine design is made up of main components including turbine shaft that is connected to electricity generator, three turbine blades that interact with incoming flow to generate rotational torque, and turbine blade arm that linked turbine blades to the main shaft and provide structural support to the rotor. The turbine design is shown in Figure 3.1, while the schematic of the turbine model (top view) is displayed in Figure 3.2. The top view of the turbine model is shown to illustrate the orientation of the turbine components relative to the flow direction that is assumed to be linear and unidirectional. The rotational motion path of the turbine blades is also illustrated with its azimuthal positions, θ ranging from -180° to +180° which represent a complete revolution. The upper semi-circle region of the flow from θ of 0° to 180° is considered as the upstream flow region, while the lower semi-circle from θ of 180° to 0° is the downstream flow region.

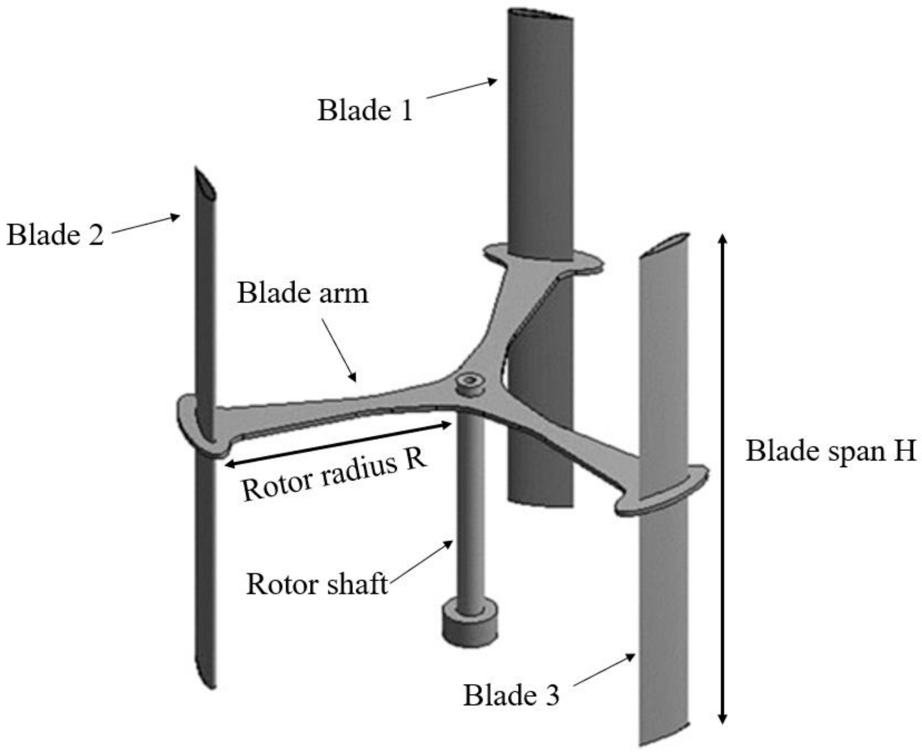


Figure 3.1: Straight-bladed Darrieus vertical axis turbine (Asr et al. 2016)

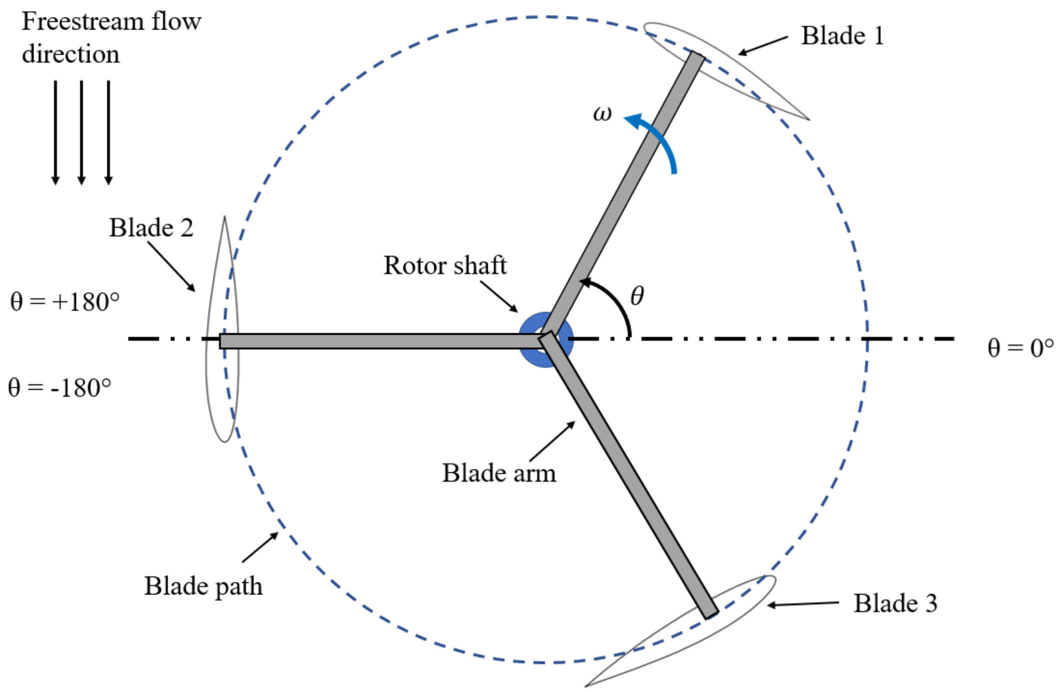


Figure 3.2: Schematic of turbine model (top view)

3.1.1. Turbine Design Specifications

A straight-bladed (H-type) Darrieus Vertical-axis Turbine was selected as the baseline model of the current investigation. The design specifications of the turbine are described in Table 3.1. The turbine with solidity of 0.5, has a rotor diameter of 1.03m, 3 blades with blade span of 1m and blade chord of 85.8mm. NACA 0021 symmetrical airfoil was selected as the blade profile of the turbine. Vertical-axis turbine was selected over horizontal-axis turbine because of its advantages including omnidirectional characteristic and scalability. Lift-based Darrieus turbine was chosen over Savonius drag-based turbine because of its relatively higher performance efficiency (Aslam Bhutta et al., 2012). Among the Darrieus turbine, Darrieus straight-bladed (H-type) turbine was selected over Darrieus parabolic blade (Φ-type) turbine because of its simpler structure without aerodynamic and structural complexities involved.

Table 3.1: Baseline turbine model design specifications

Design Specifications	**Value**
Number of Blades, N	3
Blade Profile	NACA0021
Blade Span, H	1m
Blade Chord, c	0.0858m
Rotor Diameter, D	1.03m
Turbine Solidity, σ	0.5

As mentioned in the research scope, the focus of the current investigation is the effect of different pitch angles to turbine performance. Consequently, the range of blade pitch angles applied to the turbine model are planned and set as shown in Table 3.2. Pitch angles, β were initially set between the range of -180° to +180° with interval size of 0.5°. Pitch angles that pitch the blade inwards are negative β, while β that pitch outwards are considered positive. After applying the initial pitch angle range in the optimization process, the pitch angle range was then narrowed down to the range that is involved and presented in the preliminary optimization results. The interval of pitch angle was then refined to 0.1 to produce smoother final optimization results. The large initial range was applied to utilize advantages of low order simulation to carry out investigations and simulations with large parametric range.

Table 3.2: Blade pitch angle range

Parameters	**Range**	**Interval**
Blade Pitch Angle, β	-180° to +180°	0.5° (Initial) 0.1° (Final)

3.1.2. Operating Condition

The environmental condition experienced during operation has a significant influence on turbine performance. To perform an accurate simulation, operational parametric inputs are necessary to represent the external effects from the flow. The flow medium of the current investigation was set as air under standard sea-level conditions. Airflow was chosen over water flow because the majority of the vertical-turbine axis related researches and experimental data are available in wind turbine application. However, the same turbine model can still be used for hydrokinetic applications with different operational parametric inputs. The operational parameters of the baseline turbine model are listed in Table 3.3.

Table 3.3: Operational parameters of baseline turbine model

Operational Parameters	**Value**
Freestream velocity, V_∞	9 m/s
Density, ρ	1.225 kg/m^3
Dynamic viscosity, μ	1.789 x 10^{-5} kg/m/s
Freestream Reynolds number, Re_∞	38208

Tip speed ratio (TSR), λ is the ratio of blade tip rotational velocity to the free stream velocity of the flow. For the current simulations, λ inputs determine the rotational speed of the turbine. Hence, changes in λ will affect blade relative velocity, aerodynamic loading and forces acting on the blade. Tip speed ratio range for this investigation is listed in Table 3.4. The λ was set between the range of 0.25 to 2.5, with interval size of 0.05. Since the turbine is assumed to be rotating with constant speed with no angular acceleration, such λ range indicates that the turbine rotates at minimum speed equal to freestream flow velocity and maximum speed of 2.5 times the freestream flow velocity. For every λ within the range, simulations and optimizations are carried out to analyze results with respect to λ.

Table 3.4: Turbine tip speed ratio range

Parameters	**Range**	**Interval**
Tip Speed Ratio (TSR), λ	0.25 to 2.5	0.05

3.1.3. Research Variables

This section describes the variables applied in the current investigation. These independent and dependent variables are the input and output parameters that complete the numerical simulation model. They are applied to evaluate and analyze simulated performance of turbine model under different operating condition. The variables are categorized into several sub-sections: Kinematics, Aerodynamics Coefficients, Force Coefficients, Torque and Power Generation.

<u>Kinematics</u>

Azimuthal position, θ, is the angle of turbine revolution and an independent variable to the simulation. It determines the position of turbine blades, and their relative direction to the flow. At different θ, direction of relative flow experienced by turbine blade changes.

Angle of attack, α, is the angle between blade chord line and blade relative flow direction. Similarly, angle of attack of blade changes at every azimuthal position throughout the revolution. Angle of attack influences the instantaneous aerodynamics loading and forces acting on the blade. It is a dependent variable in the current simulation model.

Blade pitch angle, β, is the angle added between blade chord line and blade relative velocity to change its angle of attack. Blade pitch angle is an independent variable of the optimization process and its effect on turbine performance is the focus of the current investigation.

Tip speed ratio, λ, as described in the previous section, is an independent variable that changes the rotational speed of the turbine. At different rotational speed, the turbine is expected to behave differently.

Aerodynamics Coefficients

Lift coefficient, C_l, of the turbine blade is a dependent variable that is influenced by blade profile selection and the blade's angle of attack. Lift coefficient will then influence the aerodynamic lift force acting on the blade

Drag coefficient, C_d, of the turbine blade is also dependent on blade profile selection and the blade's angle of attack. Drag coefficient influences the drag force acting on the blade.

Force Coefficient

Tangential force coefficient, C_t, is a dependent variable of the numerical turbine model that determine the magnitude of force component that acts on the turbine blade in direction tangential to the blade motion. Tangential force coefficient is constituted of components driven by aerodynamic lift and drag forces, C_{t_L} and C_{t_D}. It has a direct effect on turbine torque and power generation efficiency and capability.

Normal force coefficient, C_n, determine the magnitude of force component acting in the direction normal to the blade motion. It is dependent on the direction and magnitude of aerodynamic forces acting on it. Similar to its tangential counterpart, the normal force coefficient is made up of lift-based and drag-based components, C_{n_L} and C_{n_D}. Normal force acts radially and pushes against shaft bearings, influences turbine fatigue life.

Torque and Power Generation

Torque Coefficient, C_Q, is a dependent variable that determines the average torque acting on turbine blades for a complete revolution. It is highly dependent on the average tangential forces acting on the blade. The torque coefficient will then be applied to determine turbine's power generation capability.

Power Coefficient, C_P, is the ratio of power generated to the power available in the flow passing through the turbine. This dependent variable is the output parameter of turbine model simulation that evaluates the overall power performance of the turbine.

3.2. Theoretical Background

To enable accurate simulation of vertical-axis turbine, relevant equations and assumptions must be included in the numerical program. In this section, the equations and theories involved in the simulation are described.

3.2.1. Blade Element Theory

For the current numerical turbine model, Blade Element Theory is applied. Turbine blades change their azimuthal positions throughout a revolution. Thus, velocity and force components vary along the rotation path. The algorithm of the numerical model is based on the calculation of relative flow velocity through turbine blades and the aerodynamic forces generated by the blades (Islam et al., 2006). The velocity and force components are computed at each turbine blade 'element' at every azimuthal position defined in the program input. After completing a revolution, the force components of each blade element are integrated to determine the average force components acting on the blade and eventually the overall power performance of the turbine. Figure 3.3 shows the schematics of turbine blade elements at different azimuthal positions while Figure 3.4 illustrates the force and velocity components acting on a turbine blade.

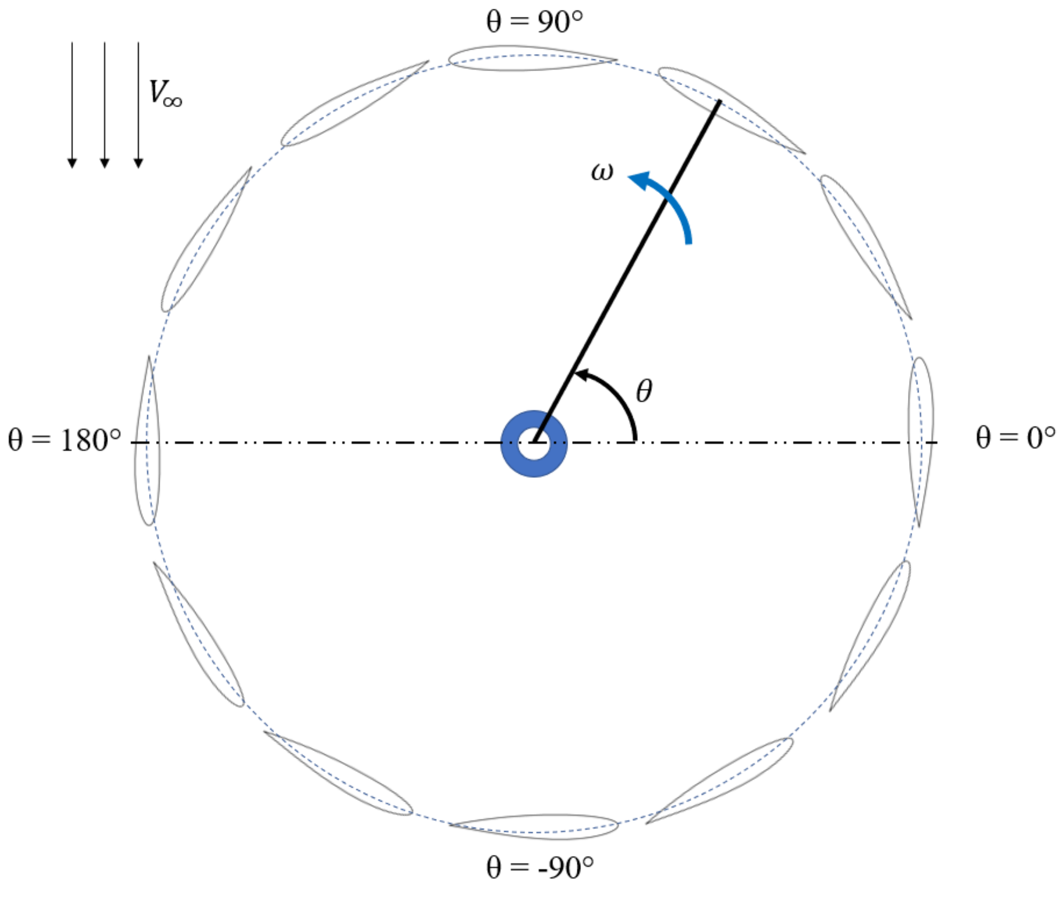


Figure 3.3: Schematic of turbine blade for a complete revolution