NUMERICAL INVESTIGATION ON THE AERODYNAMICS OF VERTICAL AXIS HYDROKINETIC TURBINES WITH SEMI-EMPIRICAL DATA

by

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ENDORSEMENT

I, FOONG XIPENG, hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

(Signature of Student)

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(Signature of Supervisor)

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Date:

(Signature of Examiner)

Name:
Date:

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 candidate for any other degree.

(Signature of Student)

Date:

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NUMERICAL INVESTIGATION ON THE AERODYNAMICS OF VERTICAL AXIS HYDROKINETIC TURBINES WITH SEMI-EMPIRICAL DATA

ABSTRACT

Renewable energy sources provide a sustainable power production for the future. Hydropower is one of the optimum choices for renewable energy extraction. Predictability, regularity and reliability make hydropower the most attractive choices for energy production. Hydrokinetic energy is harnessed from flowing streams, tidal currents and other water channels. Compared to conventional hydropower, construction of a dam or reservoir is not required due to its nature of extracting energy via water motion. Hydrokinetic turbines can be divided into two main categories: horizontal axis turbines and vertical axis turbines. For this project, attention is given to vertical axis hydrokinetic turbines (VAHTs), due to the prominence in research of horizontal axis turbines and lack thereof for vertical axis ones. VAHTs are further classified according to their different arrangements: squirrel-cage Darrieus, H-Darrieus, Curved Darrieus, Gorlov and Savonius. In this project, the H-Darrieus turbine is chosen as the model to be investigated due to its utilization of airfoil-shaped blades, thus easing the calculation of forces. For the sake of creating a mathematical model, new theories related to VAHTs are learned. Some computational models are introduced briefly, but they are not used in this investigation. Also, some previous studies which are related to the project are highlighted. Next, design methodology is prepared to aid the mathematical modelling process. The airfoil data is extracted from a previous study (s1210, NACA-0015 airfoil). The mathematical model required to compute turbine performance is formulated and shown in steps. The initial parameters are also listed. Then, details regarding the modification

of initial parameters, the in-depth study of tip speed ratio and turbine solidity, and the investigation of self-starting physics are outlined. In the end, all data acquired are displayed and plotted according to the requirements of the project. First, a baseline plot of one-blade configuration is introduced to provide a basis for comparing results. Then, plots of two-blade and three-blade turbines are made and compared to the one-blade turbine results. An in-depth look into the tip speed ratio and turbine solidity reveals that they affect the turbine similarly in outcomes but differs a little in the process. A brief insight into the self-starting physics and issues of VAHT is provided and suggestions on improving the self-starting of turbines are given. The project is then concluded with the summarization of previously covered stuff, the drawing of conclusions based on the observations and inferences, as well as suggestions provided to improve the current project and ideas for new advanced projects that can be taken in the future.

SIASATAN NUMERIKAL ATAS AERODINAMIK TURBIN HIDROKINETIK PAKSI MENEGAK DENGAN DATA SEPARA EMPIRIKAL

ABSTRAK

Sumber tenaga boleh diperbaharui memberikan pengeluaran kuasa yang mampan pada masa hadapan. Tenaga hidro merupakan salah satu daripada pilihan optimum pengekstrakan tenaga boleh diperbaharui. Kebarangkalian, keteraturan, dan kebolehpercayaan menjadikan tenaga hidro pilihan yang paling menarik bagi penghasilan tenaga. Tenaga hidrokinetik berasal daripada aliran sungai, arus pasang surut dan saluran air yang lain. Berbanding tenaga hidro konvensional, pembinaan empangan atau takungan tidak diperlukan kerana sifatnya mengekstrak tenaga melalui gerakan air. Turbin hidrokinetik dibahagikan kepada dua kategori utama: turbin paksi mendatar dan turbin paksi menegak. Untuk projek ini, perhatian diberikan kepada turbin hidrokinetik paksi menegak (VAHT) atas sebab keketaraan penyelidikan atas turbin paksi mendatar dan kekurangan bagi turbin paksi menegak. VAHT dikelaskan mengikut susunan yang berbeza: Darrieus sangkar tupai, H-Darrieus, Darrieus melengkung, Gorlov dan Savonius. Bagi projek ini, turbin H-Darrieus menjadi tumpuan siasatan atas sebab penggunaan bilah berbentuk aerofoil, memudahkan pengiraan kuasa. Demi membuat model matematik, teori-teori baru mengenai VAHT telah dipelajari. Sesetengah model komputasi diperkenalkan, namun tidak akan diguna pakai dalam siasatan ini. Beberapa kajian dahulu yang berkaitan dengan projek ini disorotkan. Seterusnya, kaedah reka bentuk disediakan bagi memudahkan proses pemodelan matematik. Data aerofoil diekstrak daripada sebuah kajian dahulu (aerofoil s1210, NACA-0015). Model matematik yang diperlukan bagi pengiraan prestasi turbin dirumuskan dan ditunjukkan

dalam langkah-langkah. Parameter permulaan turut disenaraikan. Kemudian, perincian pengubahsuaian parameter permulaan, kajian mendalam terhadap nisbah kelajuan hujung dan kekukuhan turbin, serta penyiasatan fizik penghidupan sendiri digariskan. Pada hujungnya, semua data yang diperoleh dipaparkan dan dilukis mengikut keperluan projek. Mula-mulanya, rajah baseline bagi konfigurasi satu-bilah diperkenalkan yang menjadi dasar bagi perbandingan keputusan. Seterusnya, rajah bagi konfigurasi turbin dua-bilah dan tiga-bilah dihasilkan dan dibandingkan dengan keputusan satu-bilah. Satu penyiasatan mendalam bagi nisbah kelajuan hujung dan kekukuhan turbin mendedahkan bahawa faktor-faktor ini menjejaskan turbin secara serupa dalam hasilnya tetapi berbeza dalam proses. Satu wawasan ringkas dibuat terhadap fizik dan isu penghidupan sendiri turbin dan cadangan untuk memperbaiki penghidupan sendiri turbin diberikan. Projek ini disimpulkan dengan meringkaskan perkara-perkara yang disebutkan, pembuatan kesimpulan berdasarkan pemerhatian dan inferens, dan juga cadangan bagi memperbaiki projek semasa, serta idea baharu bagi projek lanjutan yang boleh dilaksanakan pada masa hadapan.

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NOMENCLATURE

A	: projected frontal area of turbine [m^2]
C	: blade chord [m]
C_d	: blade drag coefficient
C_l	: blade lift coefficient
C_n	: normal force coefficient
C_P	: turbine overall power coefficient
C_Q	: turbine overall torque coefficient
C_t	: tangential force coefficient
CFD	: computational fluid dynamics
D	: blade drag force [N]
F_n	: normal force (in radial direction) [N]
F_t	: tangential force [N]
F_{ta}	: average tangential force [N]
H	: height of turbine [m]
HAHT	: horizontal axis hydrokinetic turbine
L	: blade lift force [N]
N	: number of blades
P	: overall power [W]
P_{max}	: maximum available power [W]
P_∞	: water pressure [Pa]
Q	: overall torque [$N\ m$]
R	: turbine radius [m]
Re	: Reynolds number

V_a	: induced velocity [$m\ s^{-1}$]
V_c	: chordal velocity component [$m\ s^{-1}$]
V_n	: normal velocity component [$m\ s^{-1}$]
V_w	: wake velocity in downstream [$m\ s^{-1}$]
V_∞	: freestream water velocity [$m\ s^{-1}$]
VAHT	: vertical axis hydrokinetic turbine
VAWT	: vertical axis wind turbine
W	: relative flow velocity [$m\ s^{-1}$]
α	: blade angle of attack [°]
γ	: blade pitch angle [°]
θ	: azimuth angle [°]
λ or TSR	: tip speed ratio
μ	: dynamic viscosity [$kg\ m^{-1}\ s^{-1}$]
v	: kinematic viscosity [$m^2\ s^{-1}$]
ρ	: fluid density [$kg\ m^{-3}$]
σ	: turbine solidity
ω	: angular velocity of turbine [$rad\ s^{-1}$]

CHAPTER 1

INTRODUCTION

This chapter provides the reader to the overview of the numerical investigations. This project is primarily motivated by the rise in renewable energy sources, especially hydropower. The performance parameters of a vertical axis hydrokinetic turbine are the main concern of this project, as detailed in the problem statements and objectives. The research scope is to perform investigations on these parameters. Finally, subsequent chapters of the thesis are outlined.

1.1 Motivation

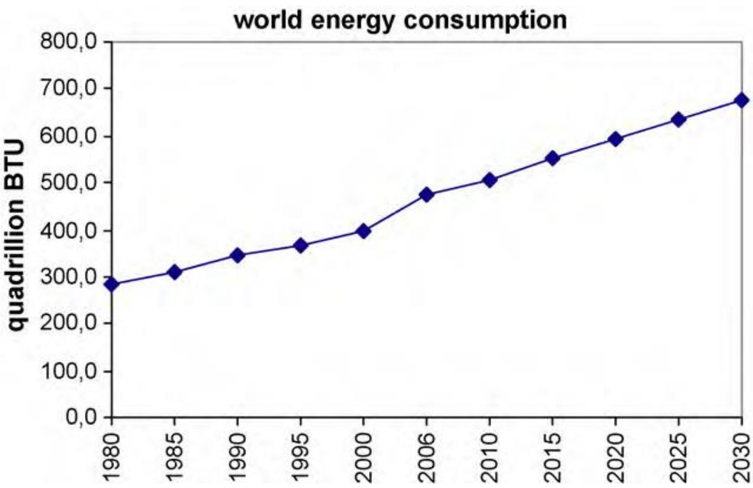


Figure 1.1: World total energy consumption with projected values. (Güney and Kaygusuz, 2010)

Increase in world population and growing demands of humankind raises the energy requirement year after year, as seen from Figure 1.1. A large portion of the energy used today originates from fossil fuels, which are declining in supply. On top of that, usage of fossil fuels causes environmental pollution and greenhouse effect. (Güney and Kaygusuz, 2010)

Renewable energy sources provide a sustainable power production in the future. Among the multiple choices for renewable energy sources, hydro and wind appear to be the optimum choices. The oceans and the rivers represent a vast untouched resource for renewable energy generation. (Güney and Kaygusuz, 2010)

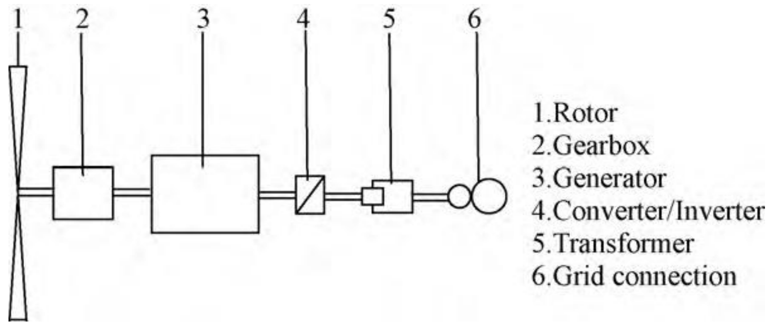


Figure 1.2: Common scheme for hydrokinetic turbine systems. (Güney and Kaygusuz, 2010)

The working principle of hydropower from water currents is shown in Figure 1.2. Hydrokinetic conversion systems, albeit mostly at its early stage of development, may appear suitable in harnessing energy from flowing river streams, tidal currents or other artificial water channels. A few resource quantization and demonstrations have been conducted throughout the world and it is believed that both in-land water resources and offshore ocean energy sector will benefit from this technology. (Khan et al., 2009)

The hydropower is the world's largest and cheapest source of renewable energy. It is also the most efficient way to produce electricity, with approximately 18% of world's electricity generated from hydropower. Predictability, regularity and having worldwide spreading sources make hydropower one of the most attractive choices of energy production across the globe. (Yuce and Muratoglu, 2015)

Hydrokinetic energy technologies have some advantages over the conventional hydropower production methods. There is no extra cost to construct a dam or a reservoir to accumulate the water, since the kinetic energy is harnessed based on water motion in the form of current and waves. Whereas hydrostatic method requires construction of reservoirs to store water to extract potential energy through suitable turbo-machinery. Although the hydrokinetic turbines have relatively small-scale power production, they can be installed as multi-unit arrays like wind farms to increase energy extraction. (Yuce and Muratoglu, 2015)

1.2 Problem Statements

There are two problem statements identified for this project:

- What are the parameters influencing turbine performance?

  The parameters of a turbine and the surrounding conditions are extremely important in determining the output performances of a turbine. As such, knowing the input and output parameters is an integral part of understanding the performance of the turbine.

- How do the parameters affect turbine performance and which parameters are of utmost importance?

  Though there exist multiple parameters affecting turbine performance, there are certain parameters that stand out due to their importance in comparing the performance of turbines. Recognising these parameters will help in obtaining evidence to support any explanations.

1.3 Objectives

To overcome the problem statements as mentioned above, two objectives are determined for this project:

- To determine the parameters influencing the performance of vertical axis turbines.

By knowing the parameters of a turbine, it is possible to observe the correlations between the input and output parameters, which in turn helps visualise the entire flow of calculations. At the same time, it can help determine which parameters are affecting the results more substantially.

- To determine the significance of standardized parameters on the outcomes of turbine performance.

  The extent of which standardized parameters, namely the tip speed ratio and turbine solidity, affect the turbine performance is investigated. Here, the importance of each parameter to adjusting turbine performance is determined.

- To investigate the self-starting physics of a turbine.

  After computing the parameters of a turbine, observations can be made on the self-starting issues of a turbine.

1.4 Research Approach and Scope

This project will cover the numerical investigations the performance of vertical axis hydrokinetic turbines (VAHTs). Initially, horizontal axis hydrokinetic turbines (HAHTs) were also considered in the coding but was eventually revoked due to severe time constraint considerations. Besides, there are plenty of research on HAHTs being carried out worldwide, while the number of studies on VAHTs pale in comparison.

To be able to perform the numerical investigations, it is essential to obtain the data for aerodynamic characteristics of airfoils. These data are originally obtained from wind tunnel experimentation results from previous studies. For the computations used in this project, several assumptions are made to ease the calculation process. The combination of experimental data and numerical assumptions develops into output parameters which are considered semi-empirical, hence the title of this thesis.

Out of all the parameters involved, two are given extra attention: tip speed ratio and turbine solidity. These parameters are known as standardized parameters, meaning the units are removed and comparisons are made using standard deviations, easing the comparison process. Once all essential data is obtained and analysed, inferences are made on the importance of both parameters on turbine performance.

Apart from the comparisons between parameters, the self-starting issue of VAHTs are examined. For this, multiple aspects are taken into consideration, such as the effect of tip speed ratio on maximum angle of attack, which in turn affects other aerodynamic parameters of the turbine blades.

Due to the few studies available in the realm of VAHTs, there are no direct verifications and comparisons of results obtained from this study to other papers. However, appropriate explanations and reasonings are made for the determination of initial parameters, and the validity of results obtained are justified according to similar studies in vertical axis wind turbines (VAWTs).

1.5 Thesis Outline

The subsequent chapters of the thesis provide full documentation on the project. Each aspect of the project is detailed, including the background required for understanding VAHTs, the methodology used for the project, the results obtained from the mathematical model and the logical inferences, as well as conclusions which can be drawn while adhering to the objectives of the project.

Chapter 2 provides the reader with quick introductions to the types of hydrokinetic turbines: the horizontal axis ones and the vertical axis ones. Next, the focus immediately shifts to the theories concerning VAHTs, which are borrowed from vertical axis wind turbine theories. Following that, several papers are introduced concerning previous studies which are somewhat related to the current study.

Chapter 3 informs the reader on how the project is conducted. Brief explanations are made on the steps of the project, including airfoil data extraction, mathematical modelling and results presentation. Each subsection provides details on how the setup of the model is conducted from start to finish.

Chapter 4 contains all the outcomes from the mathematical model, primarily in the forms of plots. For each of the plot, ample descriptions are listed, and inferences are made to explain the interesting aspects of the plot. In more specific cases, an in-depth analysis will be provided, including the study on the impact of tip speed ratio and turbine solidity on VAHT performance. Investigations on the self-starting physics of VAHT are also performed, and suggestions are made for the ideal self-starting conditions.

Finally, Chapter 5 wraps up the project. Proper conclusions are drawn based on the findings of the project, as the issues listed in the problem statements and objectives are addressed. A section detailing the future work to be done is also included, discussing the steps that can be taken to overcome the shortcomings of the current analysis, plus new ideas for extending the research in VAHTs.

CHAPTER 2

BACKGROUND

This chapter introduces the different types of hydrokinetic turbines in modern applications. The theories governing the performances of VAHTs are explained, including the illustrations, directional conventions, mathematical expressions, and several computational models. A few previous studies are also introduced, where several published papers are summarized. The studies include two papers on airfoil aerodynamic data analysis, and one paper on the self-starting physics of a wind turbine.

2.1 Theory

This subsection familiarises the reader to several concepts involved in the project. Brief introductions are made to the two main categories of hydrokinetic turbines: horizontal axis and vertical axis. Next, the theories involved in the performance of VAHTs are defined, complete with illustrations and equations.

2.1.1 Types of Hydrokinetic Turbines

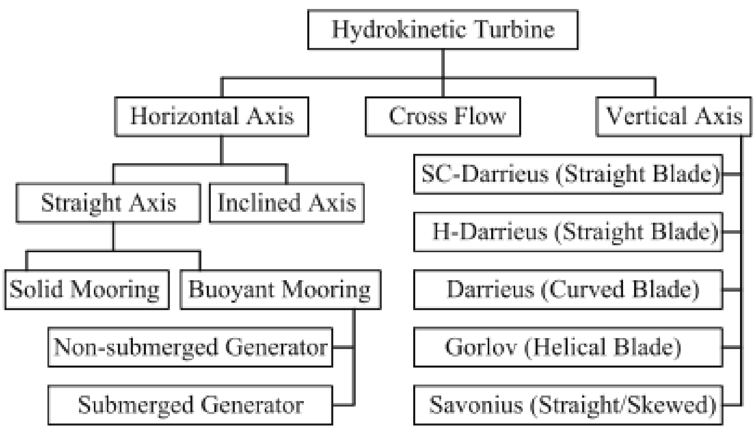


Figure 2.1: Classification of turbine rotors. (Khan et al., 2009)

The classification of hydrokinetic turbines can be divided into horizontal axis and vertical axis. (Güney and Kaygusuz, 2010; Khan et al., 2009; Yuce and Muratoglu, 2015) Figure 2.1 shows the common classification of turbine rotors.

2.1.1.1 Horizontal Axis Hydrokinetic Turbines

The rotational axis of horizontal axis hydrokinetic turbines (HAHTs), also known as axial turbines are parallel to the water current direction. HAHTs can be usually constructed as two-, three- or multi-blade. The structure can be opened or ducted. (Güney and Kaygusuz, 2010)

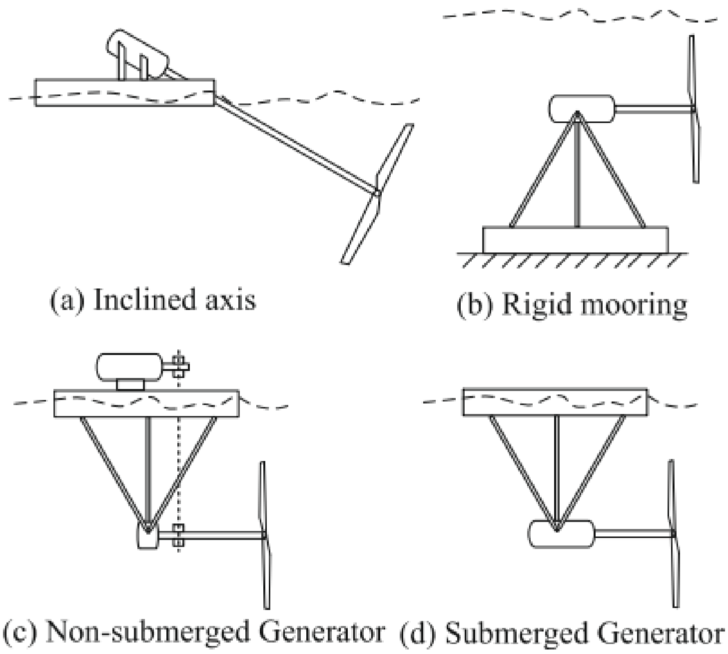


Figure 2.2: Arrangements of HAHTs. (Khan et al., 2009)

Various arrangements of HAHTs are shown in Figure 2.2. HAHTs are common in tidal energy converters and are very similar to modern day wind turbines from the concept and design point of views. Turbines with solid mooring structures require the generator unit to be placed near the riverbed or seafloor. (Khan et al., 2009)

2.1.1.2 Vertical Axis Hydrokinetic Turbines

The rotational axis of vertical axis hydrokinetic turbines (VAHTs) is perpendicular to the water surface.

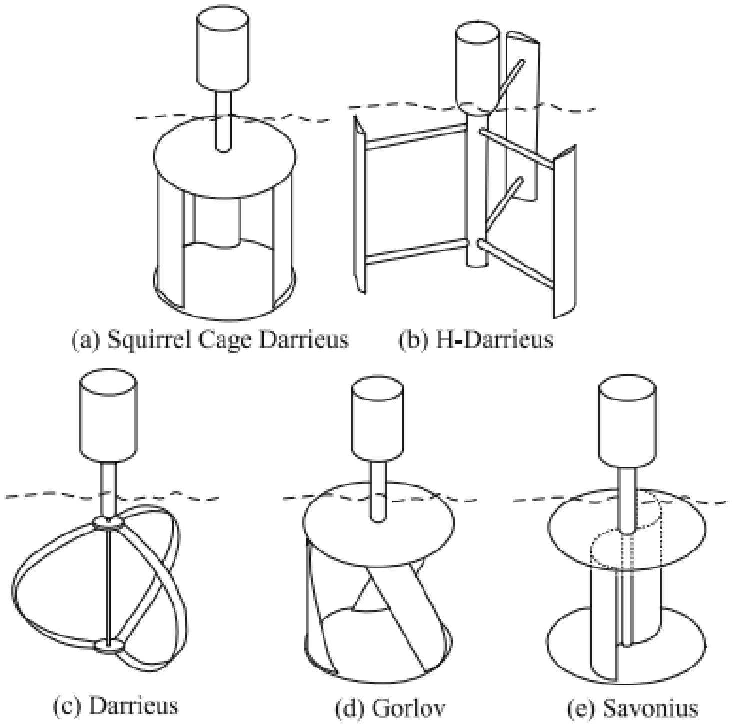


Figure 2.3: Arrangements of VAHTs. (Khan et al., 2009)

Various arrangements of VAHTs are shown in Figure 2.3. In the vertical axis domain, Darrieus turbines are the most prominent options. The usage of H-Darrieus or Squirrel-cage Darrieus (straight-bladed) turbines are very common, whereas Darrieus turbines with curved or parabolic blades is less prominent. The Gorlov turbine consists of blades that are of helical structure. Savonious turbines are drag type devices, which may consist of straight or skewed blades. (Khan et al., 2009)

2.1.2 Vertical Axis Hydrokinetic Turbine Theories

Currently, there are no papers specifically focusing on VAHT theories. However, the principles of operations VAHT resemble that of vertical axis wind turbines (VAWTs), thus the underlying theories can be carried over. This is because both air and water are fluids and behave in a similar fashion, with the main differences being the density and viscosity of the fluids.

This subsection focuses on the straight-bladed Darrieus-type VAWTs. Since the turbine uses airfoil-shaped blades, the theories applied here resemble the basic aerodynamics theories. These theories are extracted from a study on aerodynamic models for Darrieus-type straight-bladed VAWTs (Islam, Ting and Fartaj, 2008). The terms originally linked to air characteristics are modified into water characteristics.

2.1.2.1 Illustrations and Conventions

Before formulating the governing equations of the model, it is essential to visualise the movement of the turbine. To achieve this, a diagram is created to show the positions of one blade on a turbine relative to the water flow direction. Figure 2.4 illustrates eight azimuthal angles (θ) of the blade throughout one full revolution of the turbine, in increasing intervals of 45°.

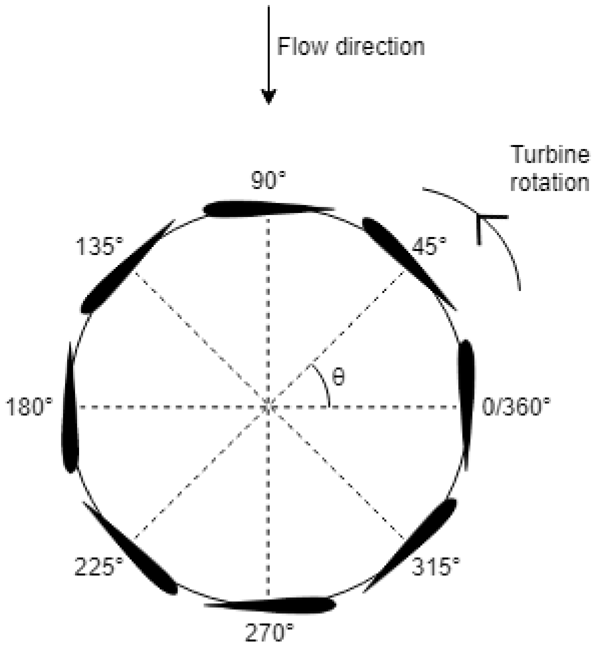


Figure 2.4: Azimuthal positions of the turbine blade relative to the flow direction.

Next, it is required to set the conventions for positive and negative values of blade angle of attack α and blade pitch angle γ, respectively. The conventions for α in connection to relative flow velocity W are shown in Figure 2.5. Similarly, the conventions for γ relative to the turbine tangential axis are shown in Figure 2.6.

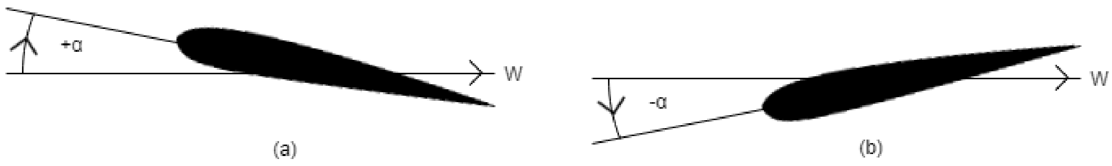


Figure 2.5: Conventions of α relative to W. (a): positive α; (b): negative α.

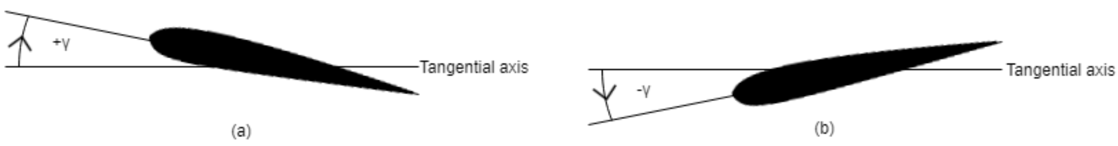


Figure 2.6: Conventions of γ relative to tangential axis. (a): positive γ; (b): negative γ.

2.1.2.2 General Mathematical Expressions

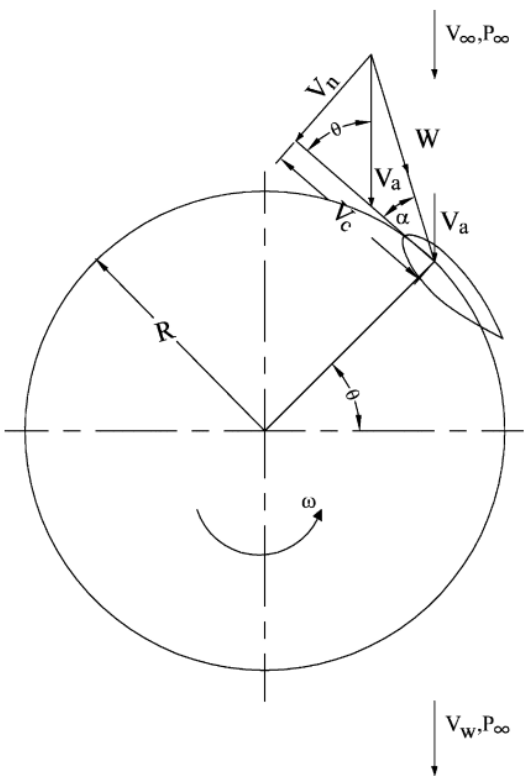


Figure 2.7: Flow velocities of a straight-bladed Darrieus-type VAWT.

From Figure 2.7, one can observe that the flow is considered to occur in the axial direction. The chordal velocity component V_c and the normal velocity component V_n are, respectively, obtained from the following expressions:

$$V_c = R\omega + V_a \cos\theta \tag{2.1}$$

$$V_n = V_a \sin\theta \tag{2.2}$$

where V_a is the axial flow velocity (or induced velocity) through the rotor, ω is the rotational velocity, R is the radius of the turbine, and θ is the azimuth angle. Also referring to Figure 2.7, the angle of attack α can be expressed as:

$$\alpha = \tan^{-1}\left(\frac{V_n}{V_c}\right) \tag{2.3}$$

Substituting the values of V_n and V_c and non-dimensionalizing:

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\left(\frac{R\omega}{V_\infty}\right)\left(\frac{V_a}{V_\infty}\right) + \cos\theta}\right) \tag{2.4}$$

where V_∞ is the freestream water velocity. If the blade pitch angle γ is considered, then:

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\left(\frac{R\omega}{V_\infty}\right)\left(\frac{V_a}{V_\infty}\right) + \cos\theta}\right) - \gamma \tag{2.5}$$

The relative flow velocity W can also be obtained from Figure 2.7:

$$W = \sqrt{V_c^2 + V_n^2} \tag{2.6}$$

Figure 2.8 shows the directions of the lift and drag forces and their normal and tangential components. The tangential force coefficient C_t is the difference between the tangential components of lift and drag forces. Similarly, the normal force coefficient C_n is the difference between the normal components of lift and drag forces. The expressions of C_t and C_n can be written as:

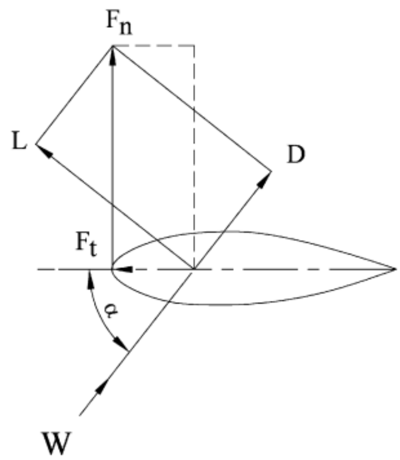


Figure 2.8: Force diagram of a blade airfoil.

$$C_t = C_l \sin\alpha - C_d \cos\alpha \tag{2.7}$$

$$C_n = C_l \cos\alpha + C_d \sin\alpha \tag{2.8}$$

where C_l and C_d are the lift and drag coefficients respectively. The net tangential and normal forces F_t and F_n can be defined as:

$$F_t = C_t \frac{1}{2}\rho C H W^2 \tag{2.9}$$

$$F_n = C_n \frac{1}{2}\rho C H W^2 \tag{2.10}$$

where ρ is the water density, C is the blade chord and H is the height of the turbine.

Equations (2.9) and (2.10) represent the instantaneous tangential and normal forces at any given azimuthal position. To find the average tangential force F_{ta} on one blade within one revolution, Equation (2.9) is integrated in terms of θ:

$$F_{ta} = \frac{1}{2\pi}\int_0^{2\pi} F_t(\theta)\, d\theta \tag{2.11}$$

The total torque Q for the number of blades N in the turbine is obtained as:

$$Q = N F_{ta} R \tag{2.12}$$

The total power P obtained is:

$$P = Q \cdot \omega \tag{2.13}$$

The maximum available power P_{max} for the turbine is defined as:

$$P_{max} = \frac{1}{2}\rho A V_{\infty}^{3} \tag{2.14}$$

where the projected frontal area of turbine A is given by:

$$A = 2RH \tag{2.15}$$

The turbine overall power coefficient C_P is defined as the ratio of produced power to available power:

$$C_P = \frac{P}{P_{max}} \tag{2.16}$$

The turbine overall torque coefficient C_Q is defined as:

$$C_Q = \frac{Q}{\rho A V^2 R} \tag{2.17}$$

Finally, there are two standardized parameters of any turbine: the tip speed ratio λ (or TSR) and the turbine solidity σ. These parameters are used to ultimately compare the performances between different turbines of different sets of parameters. They are defined by the following equations:

$$\lambda = \frac{R\omega}{V_{\infty}} \tag{2.18}$$

$$\sigma = \frac{NC}{R} \tag{2.19}$$

Another important parameter is the Reynolds number *Re*. The lift and drag coefficients data for airfoils are different from one *Re* to another. Therefore, it is crucial to first estimate *Re* before extracting the airfoil data. *Re* is defined by:

$$Re = \frac{\rho V_{\infty} C}{\mu} = \frac{V_{\infty} C}{\nu} \tag{2.20}$$

where μ is the dynamic viscosity, and ν[1] is the kinematic viscosity.

[1] Pronounced as 'nu'.

2.1.2.3 Computational Models

Several mathematical models, based on several theories, were prescribed for the performance prediction and design of Darrieus-type VAWTs by different researchers. As these models are not applied in this numerical analysis, this sub-subsection will only introduce these models briefly. Nevertheless, these models are important in predicting the velocity of flows around the turbine blades.

- Momentum model

  Momentum models (or Blade Element/Momentum (BEM) model) are based on calculation of flow velocity through turbine by equating the streamwise aerodynamic force on the blades with the rate of change of momentum of air. The force is also equal to the average pressure difference across the rotor. Bernoulli’s equation is applied in each streamtube. The main drawback of these models is that they become invalid for large tip speed ratios and for high rotor solidities because the momentum equations in these cases are inadequate.

  There are three approaches to this model: single streamtube model, multiple streamtube model, and double multiple streamtube model.

- Vortex model

  Vortex models are potential flow models based on the calculation of the velocity field about the turbine through the influence of vorticity in the wake of the blades. The turbine blades are represented by bound or lifting-line vortices whose strengths are determined using airfoil coefficient datasets and calculated relative flow velocity and angle of attack. The main disadvantage of Vortex model is that it takes too much computation time, in addition to the reliance on significant simplifications.

- Cascade model

  In this model, the blade airfoils of a turbine are assumed to be positioned in a plane surface (termed as the cascade) with the blade interspace equal to the turbine circumferential distance divided by the number of blades. The aerodynamic characteristics of each element of the blade are obtained independently for the upwind and downwind halves of the rotor. This model can predict the overall values of both low and high solidity turbines quite well. It takes reasonable computation time. It does not make any convergence problem even at the high tip speed ratios and high solidities.

2.2 Previous Studies

In this subsection, several previously published papers related to this project are highlighted in detail. The studies are divided into two categories: airfoil aerodynamic data investigations, and self-starting physics of a wind turbine.

2.2.1 Airfoil Aerodynamic Data Analysis

The first paper (Stringer et al., 2018) presents a model for predicting aerodynamic forces acting on the s1210 airfoil at two low Reynolds-number conditions (5×10^4 and 10^5). This model is based upon results from wind-tunnel experimentation and achieves a close approximation of the measured performance of the airfoil. It provides the means to predict airfoil lift and drag characteristics and the thrust capabilities of the airfoil as the turbine blades rotate.

The airfoil used, s1210 airfoil (Figure 2.9) is highly cambered, where previous studies suggested that it can aid VAWT devices in self-starting. It also provides high lift at low Reynolds numbers.

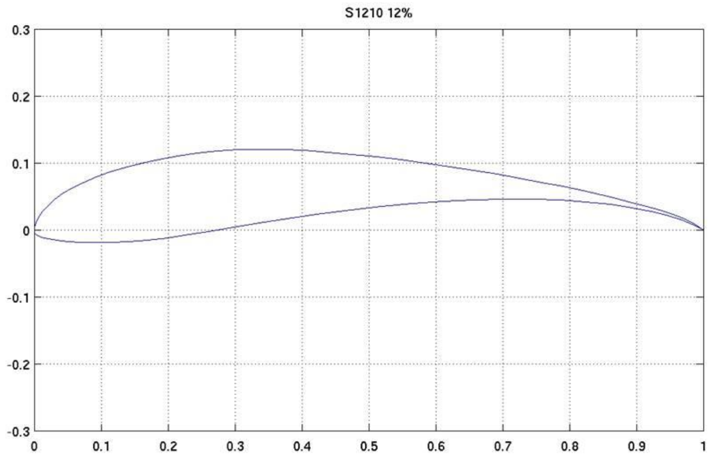


Figure 2.9: s1210 airfoil.

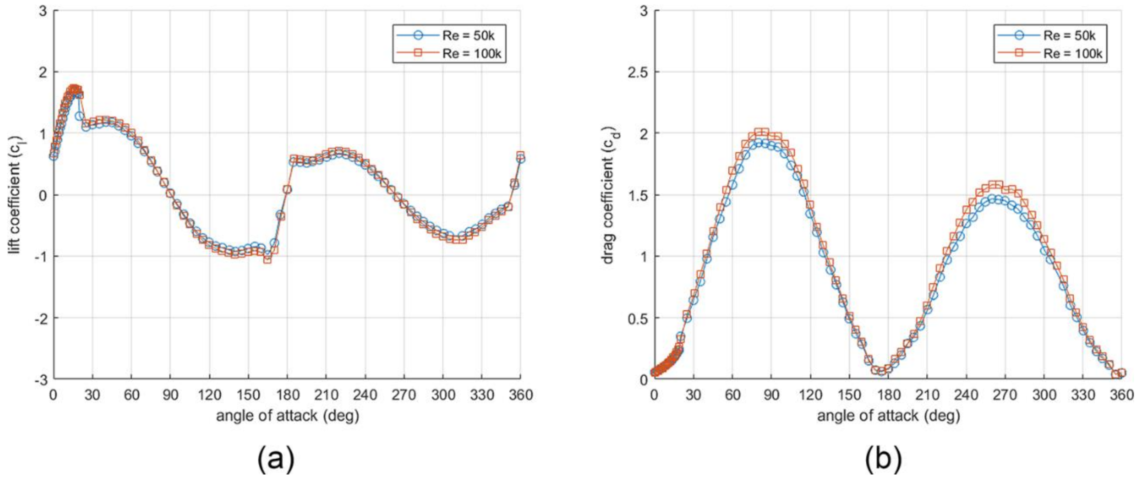


Figure 2.10: s1210 average (a) lift and (b) drag coefficient data.

The average lift and drag coefficient data versus angle of attack are presented in Figures 2.10(a) and 2.10(b), respectively. Using these data for thrust prediction, two angle of attack regions, one between 0° and 30° and the other between 180° and 300° provide the highest thrust contributions of the airfoil.

Compared to other post-stall models mentioned in the paper, it is shown that this model is superior to previous models when applied to the s1210. Using models such as this for system-level analysis provides the means to assess the feasibility of different VAWT configurations. This enables the designer to determine the optimum turbine geometry to maximize performance.

The second paper (Sheldahl and Klimas, 1981) describes a wind tunnel test series conducted at moderate values of Reynolds numbers in which lift, drag and moment coefficients data at $0 < \alpha < 180°$ were obtained for four symmetrical blade candidate airfoil sections (NACA-0009, -0012, -0012H, and -0015). It also shows how an airfoil property synthesizer code can be used to extend the measured properties to arbitrary values of Reynolds numbers ($10^4 \leqslant Re \leqslant 10^7$) and to certain other section profiles (NACA-0018, -0021, -0025).

In the report, multiple tables contain data for lift and drag coefficients for airfoil sections NACA-0012, -0015, -0018, -0021, and -0025 at $10^4 \leqslant Re \leqslant 10^7$. There are also figures containing plots of lift, drag, moment and axial force coefficients against angles of attack (sectional and full-range) for the NACA-0009, -0012, -0012H, and -0015 airfoil sections. Selected samples for lift and drag coefficient plots for the NACA-0015 airfoil are shown in Figures 2.11 and 2.12.

A brief section in the report explains how the obtained data is used in adequately predicting VAWT performance.

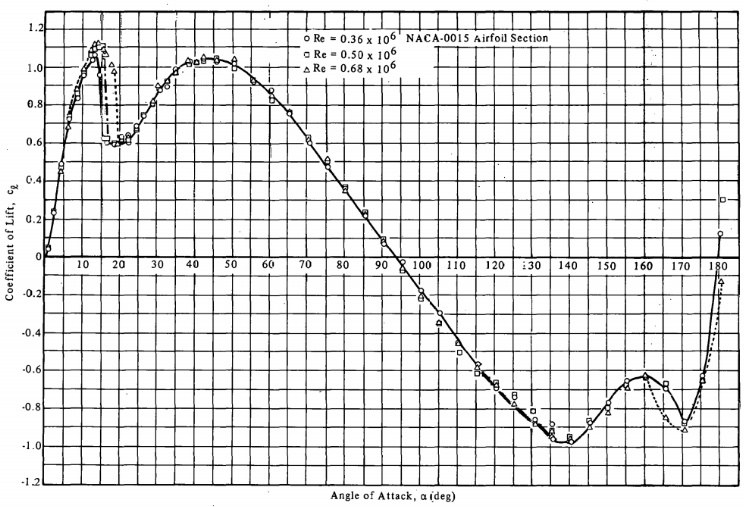


Figure 2.11: Half-range section lift coefficients for the NACA-0015 airfoil.

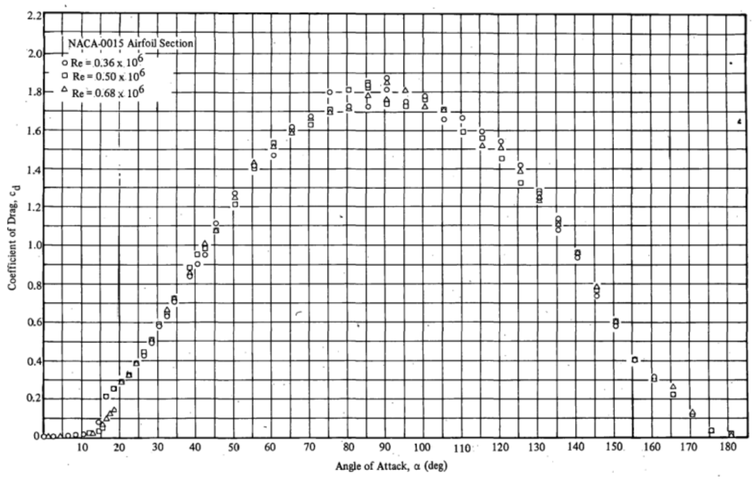


Figure 2.12: Half-range section drag coefficients for the NACA-0015 airfoil.

2.2.2 Analysis of Self-Starting Physics

The purpose of study in the paper (Douak et al., 2018) is to project an optimized Darrieus-type VAWT capable to start at low wind speeds. The study consists of three parts:

- A system of monitoring and control of the angle of attack that allows a self-starting at low wind speeds.

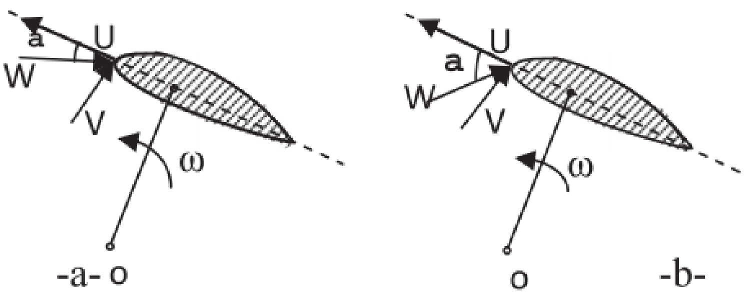


Figure 2.13: Angle of attack on rotating blades at (a) normal operating conditions and (b) at low rotational speed.

The paper has considered a mechanism that lets the blades be pivoted during their rotation such that they always show the relative wind maximum incidence and that the starting torque is increased. In Figure 2.13(a), under normal operations the angle of attack always remains smaller than the stalling angle and thus the wind produces a useful lift force. At low rotational speed in Figure 2.13(b), the tip speed ratio is low, and the angle of attack increases causing the aerodynamic stall of the blade.

- A general method for obtaining a profile with good starting torque.

Knowledge of the pressure coefficient provides information on the contribution of drag and therefore it is possible to see the blade profile segments who suffer from drag forces. This way, it is possible to see the contribution of the resistance forces in forward motion of the blades or in the opposite direction, respectively.

- The experimental study of the impacts of the angle of attack, the solidity and the wind velocity on the lift, drag forces and torque.

Small TSR leads to large angle of attack, and once it overtakes the static stall angle of airfoils (about 12–15°), the torque and power coefficients drop drastically. Meanwhile at very high TSR, the angle of attack will become too small, also resulting in low values of the torque and power coefficients.

In Figure 2.14, it is shown that the maximum value of power coefficient increases with the solidity parameter.

The experimental results concerning the lift forces, drag forces and torque coefficients are shown in Figure 2.15. Increasing wind speed causes an increase in lift force (Figure 2.15(a)) and a decrease in drag force (Figure 2.15(b)), with an anomaly at $\alpha = 6°$. The combination of lift and drag forces into torque is at maximum at all wind speeds when $\alpha = 15°$ (Figure 2.15(c)).

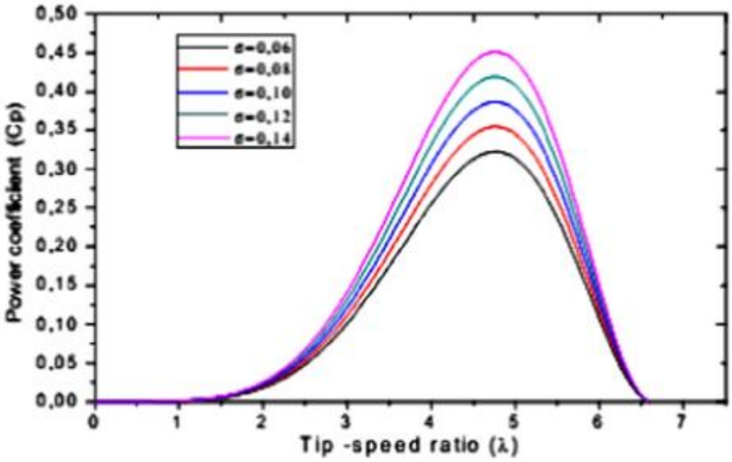
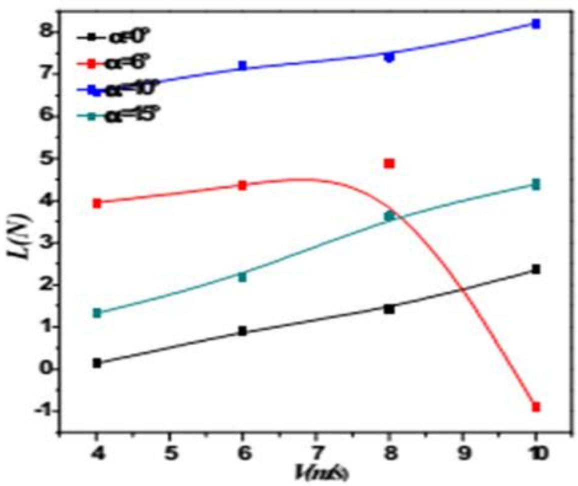
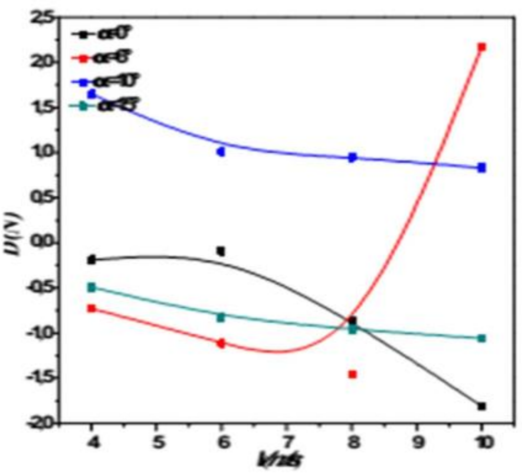


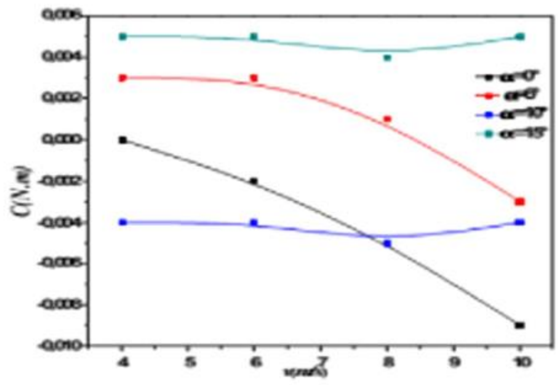
Figure 2.14: Power coefficient versus tip speed ratio for different values of solidity.



a



b



c

Figure 2.15: Experimental results on effects of wind speed on (a) lift force, (b) drag force, and (c) torque coefficient.

CHAPTER 3

METHODOLOGY

This chapter provides elaboration on how the full numerical analysis works from start to finish. A mathematical model is formulated to speed up the analysis process. Part of the model requires the input of airfoil aerodynamic data, which is extracted using an external software and then implemented into the model. With the data available, the model is then constructed based on the governing equations of the theories. After inputting the initial parameters, the model is applied to perform calculations for outputting parameters. The required data according to project objectives are presented using graphical plots to ease the visualization of data. Depending on the requirements of the investigation, the initial parameters are modified to achieve the desired results for data comparison purposes.

3.1 Airfoil Data Extraction

Before beginning the numerical analysis, data for lift and drag coefficients C_l and C_d against angle of attack α are required. These data are extracted from previous studies as described in Subsection 2.2.1.

Since different values of Re will affect the lift and drag coefficient plots, it is first necessary to estimate the Reynolds number of the model. Recalling Equation (2.20):

$$Re = \frac{\rho V_\infty C}{\mu} = \frac{V_\infty C}{\nu} \tag{2.20}$$

There are two known constants: ρ = 998.2 $kg\ m^{-3}$ and $\mu = 1.005\times10^{-3}$ $kg\ m^{-1}\ s^{-1}$ at room temperature (20 °C). For this model, it is assumed that V_∞ is a constant 1 $m\ s^{-1}$. For C, the value changes due to the varying turbine solidity (see Section 3.2) but is estimated to be around 0.1 m.

Re is therefore estimated as:

$$Re = \frac{\rho V_\infty C}{\mu} = \frac{(998.2)(1)(0.1)}{1.005 \times 10^{-3}} = 99323 \approx \mathbf{10^5}$$

Once *Re* is estimated, extraction of aerodynamic data for $0 \leq \alpha \leq 360°$ from the papers is performed.

Aerodynamic data data for s1210 airfoil (Stringer et al., 2018) is only available in graphical plots. It is therefore required to extract the data into tabular format. This is performed using a software called Plot Digitizer. Here, data for $Re = 10^5$ is extracted.

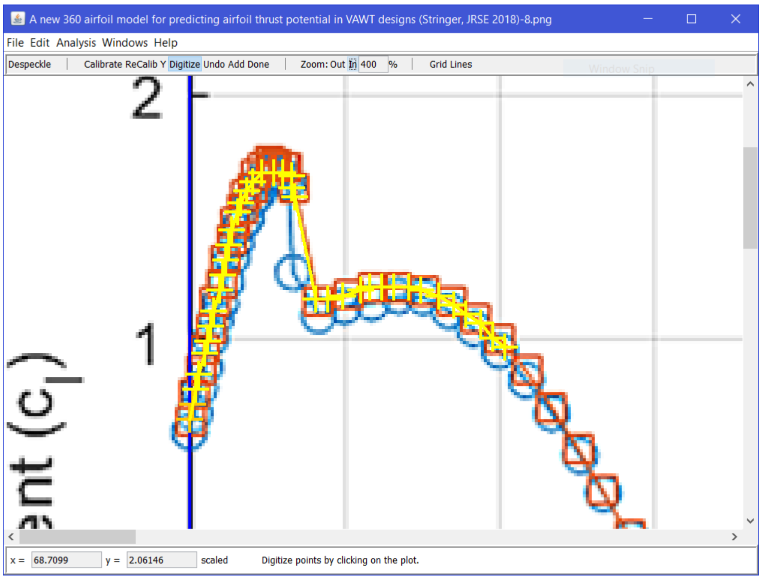


Figure 3.1: Selecting points to extract data in Plot Digitizer.

Figure 3.1 shows the process of extracting data using Plot Digitizer. The program first requires the user to calibrate the x- and y-axes, and then labelling and specifying the minimum and maximum values for the axes. Next, the plot points on the graph are selected carefully. Once all the points are selected, the data is displayed in a new box, and the user can opt to save the extracted data in .csv[1] format.

[1] A comma-separated values (CSV) file allows data to be saved in a table structured format. Traditionally they take the form of a text file containing information separated by commas, hence the name.

For the NACA-0015 airfoil (Sheldahl and Klimas, 1981), the airfoil data are properly listed in tables, which can be directly obtained. Data at $Re = 10^5$ is not available, so the data for the next closest value (Re = 80000) is obtained instead. Also, data is only available for $0 \leq \alpha \leq 180°$. For the range $180° < \alpha \leq 360°$, the table is inverted such that data at α equals to data at $(360°-\alpha)$. This can be done since the airfoil is symmetric.

All extracted lift and drag coefficients data in tabular form can be found in Appendix A.

3.2 Mathematical Model Formulation and Application

The computation flow of the mathematical model is summarised in Figure 3.2. The model is created using MATLAB programming.

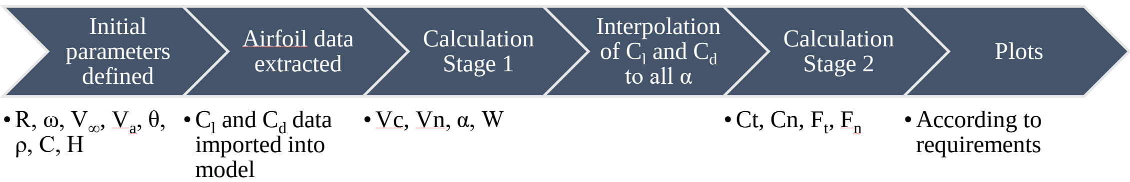


Figure 3.2: Computational flow of the mathematical model.

Table 3.1 lists the parameters of the environmental conditions of the turbine. These parameters are assumed to be always constant to reflect the stable environmental conditions around the turbine. Table 3.2 lists the initial parameters of the turbine itself. Once the first set of data is computed, some of the parameters here can be modified to achieve a different set of results.

Table 3.1: Parameters for the turbine environment.

Parameter	Value
Temperature of water	20°*C*
Density of water, ρ	998.2 $kg\ m^{-3}$
Dynamic viscosity, μ	1.005×10^{-3} $kg\ m^{-1}\ s^{-1}$
Freestream velocity, V_∞	1 $m\ s^{-1}$
Axial flow velocity, V_a	0.75 $m\ s^{-1}$