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EXPERIMENTAL STUDY ON THE PERFORMANCE OF VERTICAL AXIS HYDROKINETIC TURBINE IN REALISTIC STREAM CONDITION

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by

NG WEI QUAN

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ENDORSEMENT

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

(Signature of Student)

Date:

(Signature of Supervisor)

Name:

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 candidature for any other degree.

(Signature of Student)

Date:

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EXPERIMENTAL STUDY ON THE PERFORMANCE OF VERTICAL AXIS HYDROKINETIC TURBINE IN REALISTIC STREAM CONDITION

ABSTRACT

Research on hydrokinetic turbine is increasing due to the energy demand by human being is increases. A small-scale, 13cm diameter, Vertical Axis Hydrokinetic Turbine (VAHT) designed, fabricated and equipped with rotational speed measure device to investigate the aerodynamic behaviour of the VAHT in a laboratory setting to study the effect of parameter changes and fluid structures. Vertical Axis Hydrokinetic Turbine is a facility that extract energy from moving water stream to generate electricity. The VAHT able to perform a maximum rotational speed of 113.87 RPM at flow speed of 0.45m/s with a force-start motion. In the second part of this work, the adjustable design of the laboratory turbine enables operations with different number of blades, 1, 2, 3 and 4 blades, and present pitch angles, 0° and ±2°. Investigation of the effect of pitching angle and number of blade to the instantaneous rotational speed of the turbine is done by experimental method. Results indicate that toe-out pitch angle increases the rotational speed of the VAHT and shorten the time required to reach maximum rotational speed. As expected, decreasing number of blades will reduce the self-starting ability and increase the oscillation amplitude. However, the overall rotational speed will increase. In the third part of this work, low self-starting characteristic of VAHT was been studied in qualitative and quantitative method. The flow pattern of the water flow toward the VAHT was observed by using dye injection flow visualization method. The flow after upstream blade produces a large scale of wake and affect the performance of the downstream blade. The torque behaviour among 360° azimuth angle of the turbine is investigated by setting up 1-blade turbine in the water channel. There is only a region of azimuth angle that produces positive and useful torque to the VAHT. Next, the rotational speed of VAHT from initial stationary state and continues until the final steady-rotational condition is recorded to study its self-starting trend. As tip speed ratio lower than 1, VAHT shows a struggling behaviour to rotate in this critical region. Once the positive torque exceed negative torque, then VAHT able to rotate to its maximum Tip Speed Ratio.

KAJIAN EKSPERIMENTAL MENGENAI TURBINE HYDROKINETIK BERPAKSI VERTIKAL DALAM ARUS AIR YANG REALISTIK

ABSTRAK

Penyelidikan mengenai turbine hidrokinetik meningkat disebabkan permintaan tenaga elektrik oleh manusia meningkat. Vertical Axis Hydrokinetic Turbine (VAHT) yang saiz 13cm diameter telah direka dan dilengkapi dengan alat pengukur kelajuan putaran untuk menyelidik tingkah laku aerodinamik VAHT. Axis Vertical Hydrokinetic Turbine adalah satu kemudahan yang mengeluarkan tenaga kinetik dari arus air bergerak untuk menghasilkan tenaga elektrik. VAHT yang direka dapat melakukan kelajuan putaran maksimum sebanyak 113.87 RPM pada kelajuan air aliran 0.45m/s. Seterusnya, reka bentuk turbine hidrokinetik yang boleh laras ini membolehkan operasi tukar reka bentuk dengan bilangan bilah iaitu 1, 2, 3 dan 4 bilah, dan sudut pitching, 0° dan ±2°. Keputusan menunjukkan bahawa sudut pitching meningkatkan kelajuan putaran VAHT dan memendekkan masa yang diperlukan untuk mencapai kelajuan putaran maksimum. Seperti yang dijangkakan, bilangan bilah yang semakin meningkat akan mengurangkan kemampuan diri untuk putaran dan meningkatkan amplitud ayunan. Walau bagaimanapun, bilangan bilah meningkat dapat meningkatkan kelajuan pusingan keseluruhan. Dalam bahagian ketiga ini, ciri-ciri kemampuan diri untuk putaran oleh VAHT yang rendah telah dikaji dalam kaedah kualitatif dan kuantitatif. Corak aliran air ke arah VAHT diperhatikan dengan menggunakan kaedah visualisasi aliran suntikan pewarna. Aliran selepas bilah akan menghasilkan skala pergolakan yang besar dan menjejaskan prestasi bilah bahagian belakang. Tingkah laku tork di 360° sudut azimut turbine telah diselidiki dengan menubuhkan turbin 1-blade di saluran air. Terdapat hanya sudut azimut kecil yang menghasilkan tork positif dan dapat menyumbang kepada

VAHT. Seterusnya, kelajuan putaran VAHT dari keadaan permulaan dan berterusan sehingga keadaan mantap putaran direkodkan untuk mengkaji trend kemampuan diri untuk putaran. Semasa nisbah kelajuan tip rendah daripada 1, VAHT menunjukkan tingkah laku bergelut untuk berputar di kawasan kritikal ini. Tetapi apabila tork positif melebihi tork negatif, maka VAHT dapat berputar ke Tip Speed Ratio maksimum.

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LIST OF ABBREVIATIONS

VAHT : Vertical Axis Hydrokinetic Turbine

HAHT : Horizontal Axis Hydrokinetic Turbine

VAWT : Vertical Axis Wind Turbine

HAWT : Horizontal Axis Wind Turbine

TSR : Tip Speed Ratio

fps : Frame Per Seconds

AOA : Angle of Attack

CFD : Computational Fluid Dynamic

LIST OF SYMBOLS

P_{in} : Power Input [Watt]

A : Surface Area [m^2]

ρ : Density [kg/m^3]

V : Water Velocity [m/s]

C_p : Power Coefficient

R : Turbine Radius [m]

ω : Angular Speed [rad/s]

V_r : Resultant Velocity [m/s]

θ : Azimuth Angle [Degrees]

σ : Solidity

N : Number of Blades

c : Blade Chord Length [m]

Re_b : Blade Reynold’s Number

K_v : Kinematic Viscosity [m^2/s]

α : Angle of Attack [Degrees]

Cn : Normal Force Coefficient

Ct : Tangential Force Coefficient

Cl : Lift Coefficient

Cd : Drag Coefficient

T : Torque [Nm]

n : Revolution per Second [RPS]

P_{out} : Power Output [Watt]

C_p : Power Coefficient

β : Pitching Angle [Degrees]

s : Span of The Blade [m]

d : Diameter of The Blade [m]

V_{mean} : Mean Flow Velocity of The Cross Section of Test Section [m/s]

V_{rms} : Root-Mean-Square Velocity of the Velocity Fluctuations of the Cross Section of Test Section

$I_{turbulence}$: Turbulence Intensity

CHAPTER 1

INTRODUCTION

This project is to conduct an experiment to study the performance of Vertical Axis Hydrokinetic Turbine(VAHT) in realistic stream condition. Hydrokinetic turbine is a facility that able to extract the energy from the moving water stream and convert to the electrical energy. Furthermore, it converts kinetic energy from the water stream to mechanical energy. The mechanical energy will rotate the turbine and this mechanical energy will converted to electrical energy through generator. Vertical Axis Hydrokinetic Turbine as known as VAHT in short is the turbine that the rotational axis is parallel to the water stream direction. Realistic stream condition represents the water flow condition is in turbulence condition. In this chapter, there are five sub-section will be presented. The five sub-section includes motivation, problem statement, objectives, research approach and scopes and thesis outline. The motivation behind the project and the important of the project is discussed in motivation section. Followed by problem statement and few objectives will be determined. Next, research approach and scopes explain the direction of the project. Lastly, thesis outline is to describe the chapter list of this thesis in a brief.

1.1 Motivation

From figure 1.1, the energy consumption in global market is increasing dramatically every year. Its due to the demand of energy from human is increasing. There are a few ways to obtain energy, such as nuclear, natural gas, coal, and renewable energy (solar, wind, hydroelectric etc.). At past decade, human tends to obtain energy by using non-renewable energy such as natural gas and coal. The advantages of these non-renewable energy are easy to obtain and large energy can be produced. However, the disadvantages of using natural gas or coal are raw material like coal or natural gas will be finishing up in future. Besides that, dominating energy supplies such as non-renewable energy will increase the growth in emission of carbon dioxide (CO_2) because of increased use of fossil fuels, for example, coal, oil, and gas.

The emission of carbon dioxide will increase the global average temperature. In order to overcome those issue come from non-renewable energy, people figure out a solution which replaces natural gas or coal by using renewable energy. The reason for choosing renewable energy is because of the extraction of the energy is an unlimited and low impact on the environment. If renewable energy is properly implemented, this type of energy is able to lead us to better access to energy, a safer energy supply, and without any negative impact on the environment.

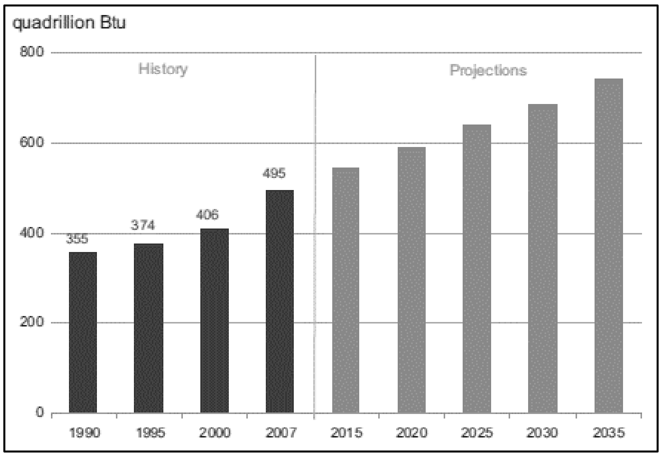

Figure 1.1 World market energy consumption 1990-2035 (Güney, 2011).

Based on Figure 1.2, the demand of renewable energy will increase. Currently the most used renewable energies are hydro and wind. However, a hydrostatic turbine requires a dam to accumulate water and use the potential energy of water to generate electricity. As a result, it will destroy habitats of animals and the environment. While the blade of the wind turbine has to build in a big scale for it to extract sufficient power from the wind. Due to this weakness of hydrostatic and wind turbine, hence hydrokinetic turbine is better and user-friendly. Hydrokinetic turbine requires a small area and does not require a dam or a reservoir. Therefore, the impact on the environment is much lower than hydrostatic power. Furthermore, water density is higher than air density. Thus, the power that water stream could extract will be higher than wind flow. In addition, hydrokinetic turbine has a number of advantages compared with other renewable energy extraction technology. Water is one of the abundant renewable resource covering over 75% of the earth. This proves that water resource is unlimited and can be extracted easily. Recent studies have shown the increase of hydrokinetic energy usage which will show at figure 1.3 (Kaur, 2016). Hydrokinetic Turbine requires only the flow of water to generate electrical power and implies that it is suitable for vary situations such as river and ocean. Therefore, it is essential to study the working principles of it and develop it (Güney, 2011).

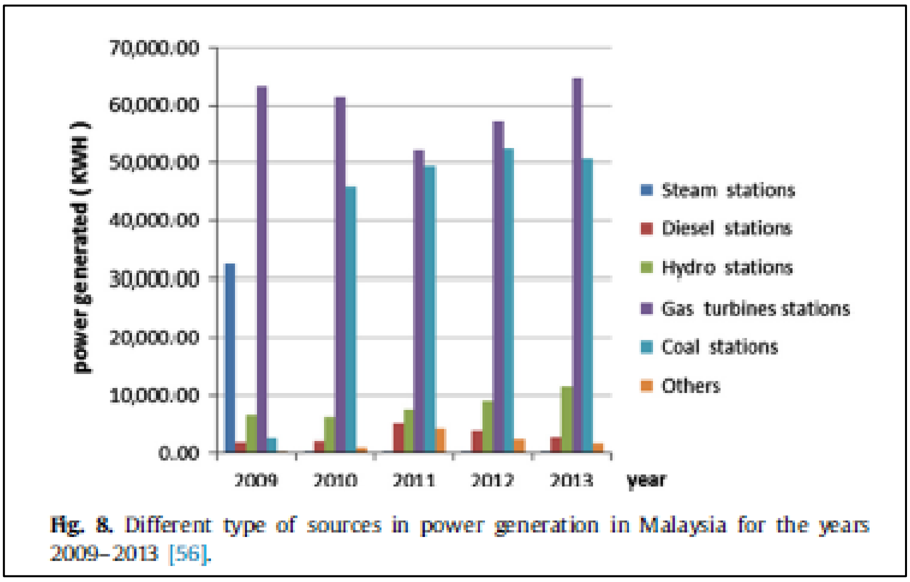

Figure 1.2 World net electricity generated by 2009 to 2013 (Güney, 2011).

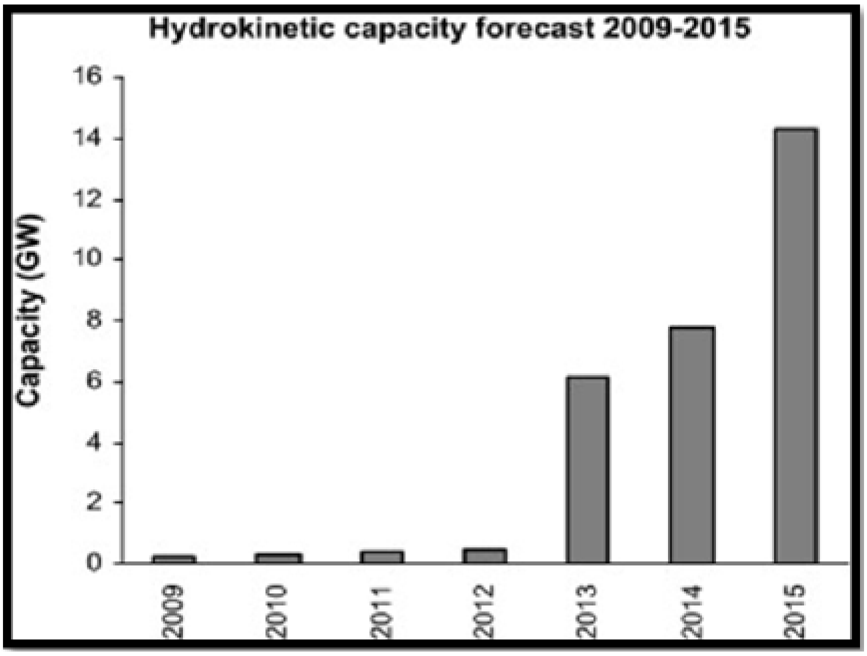

Figure 1.3 Hydrokinetic Energy forecast from 2009 to 2015 (Kaur, 2016).

1.2 Problem Statement

There are two types of hydrokinetic turbine. They are horizontal axis and vertical axis. Horizontal axis (axial) turbine’s water flow direction that is parallel to the rotational axis of the turbine, while vertical axis (cross flow) turbine’s water flow direction is perpendicular to the rotational axis of the turbine. In rural area, the conditions of river water flow characteristic are unsteady and skewed. Therefore, vertical axis hydrokinetic turbine is suitable at river application. In addition, the characteristic of vertical axis hydrokinetic turbine is omni-direction as well as having a convincing performance in the turbulence water flow. Hydrokinetic turbine is basically an extraction energy method from moving water flow. The first form is the energy from moving water causing the blade of the VAHT to move in a circular motion. Therefore, kinetic energy from moving water becomes mechanical energy of the turbine. From there, the shaft of the turbine will rotate the generator and electrical energy will be generated. From mechanical energy to electrical energy process, there are many types dynamo generator in market. Thus, this paper will focus on how the kinetic energy from moving water is converted to the mechanical energy of turbine. Furthermore, the efficiency of vertical axis hydrokinetic turbine is lower than horizontal axis hydrokinetic turbine. Horizontal turbine has a better efficiency due to its symmetrical performance at the rotational axis. While vertical turbine has the angle of attack variation in the azimuth angle and blades experience a load with a chance of dynamic stall happen. Furthermore, the blade wake interaction in the downstream part increases the complexity of the flow. It is important to study the performance of the VAHT under different parameters. Many researchers have studied the parametric effect to the performance of VAHT. However there is lack of experiment study on parametric effect to increase performance of the vertical axis hydrokinetic. There is also a gap of the optimum turbine configuration (dimensions, solidity and the blade shape). In addition, numerous research study the performance of turbine in a uniform flow which it is not realistic. The hydrokinetic turbine normally will be placed in the river or ocean which the flow would not be uniform flow. Thus, it is important to document all the effect of the parametric turbine design to the turbine performance under the realistic stream condition.

In the past, a number of studies about the vertical axis hydrokinetic turbine have been carried out. There is an issue that will face on vertical axis hydrokinetic turbine which is low self-starting issue. Low self-starting issue means that the turbine cannot be self-start rotate unless there is enough water stream energy. In fact, there are various numerical study about self-starting characteristic for vertical axis turbine (Mohamed *et al*., 2017, Arab *et al*., 2017). However most of the studies were performed in a two-dimensions numerical way to understand the self-start characteristic. In reality, condition the blade tip of the turbine will affect the turbine performance. Thus, it is important to analysis in a three-dimensional. Besides, VAHT normally operates in the river or ocean area, it is important to research on the self-starting characteristic of VAHT in the realistic stream condition instead of uniform flow condition. In addition, due to the similarities of self-starting characteristic between Vertical Axis Wind Turbine and Vertical Axis Hydrokinetic Turbine, many researchers chose to research on the Vertical Axis Wind Turbine

Therefore, the problem statements of this project are shown below.

i. How is the performance of the vertical axis hydrokinetic turbine under the simulated realistic river flow?
ii. What is the factor that causing Vertical Axis Hydrokinetic Turbine VAHT having low self-start issue?

1.3 Objectives

Firstly, on solving the problem, the main goal is to understand the performance of a vertical axis hydrokinetic turbine under realistic stream condition. Before measuring its performance, the VAHT has to be designed and tested in the water channel. The dimension of the turbine has in a size that is able to insert into the test section of the water channel. The main function of the turbine is the ability to rotate in the simulated stream condition water channel. Moreover, the turbine is able to vary the design parameter, such as pitching angle and the number of blades. The performance of the turbine under different parameters have to be measured under a simulated stream condition. Therefore, several experiments will be conducted to measure rotational speed of the turbine and the water flow velocity. The experiments will be conducted in a water channel that is build by Tong Poh Eng. Furthermore, the experiment will be focusing on measuring the rotational speed of the turbine with different number of blades and its pitching angle under a simulated realistic stream condition.

The secondary goal of this research is to study the factor that causes low self-starting characteristic of the turbine. The experiment will be conducted in a water channel with dye injection. The flow visualization will be performed by using dye injection. In this experiment, one bladed turbine will be used to determine the effect of dynamic flow behaviour at the bladed at different azimuth angle. The flow patterns are used to study the dynamic flow behaviour of the water stream when passing through the blade of the turbine. Besides that, quantitative measurement will be conducted by measuring the angular speed at every azimuth angle and every second. The qualitative and quantitative data were used to analysis the factor of low self-starting of the turbine.

Hence, research objectives are as below:

i. To design a functioning Vertical Axis Hydrokinetic Turbine.
ii. To study the performance of the Vertical Axis Hydrokinetic Turbine under the realistic stream condition.
iii. To study the factor that causes low self-starting of VAHT.

1.4 Research Approach and Scopes

1.4.1 Approach

In this project, a Vertical Axis Hydrokinetic Turbine range of size 13 cm will be designed. Furthermore, the hydrokinetic turbine will be designed to have certain function. The first function is the ability to rotate in the simulated realistic stream condition. The second function is the different number of blades in the turbine. The last function is the blade pitching angle can be varied. The reason of this design is to study the effect of blade number and blade pitching to the rotational speed of the turbine.

Two approaches will be performed in this research which are quantitative and qualitative method. For quantitative method, the VAHT will be inserted into the water channel and rotational speed will be measured. Video recording method will be used to measure the rotational speed of the VAHT. Furthermore, the video will be recorded in the 1020 resolution 120fps file and then converts to multiple images at the rate of 1 second of video to 120 images. Every image has a time interval of 1/120 seconds. Next, the angular speed will be analysed by looking at the image one frame at a time. The experiment set up is shown in figure 1.4. The turbine will be held by a bearing. One 360 degrees protractor will be placed above the transparent platform and video camera will record the motion of the pointer toward the protractor.

Next, flow visualization on the flow pattern of water stream relative to the blade is the qualitative approach for this research. The top plate of the turbine will be designed to be transparent to visualize the flow pattern easily. To record the flow pattern, a video camera will be placed above the turbine to record the flow pattern of the dye when passing through the blade as shown in figure 1.4.

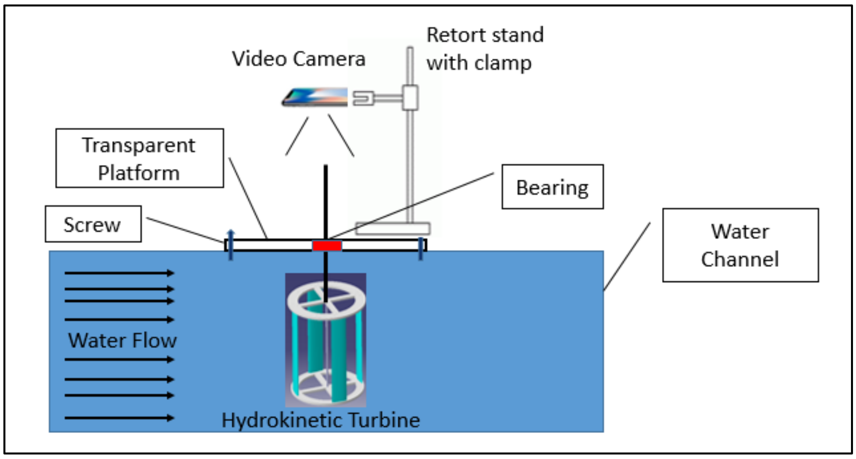

Figure 1.4 Experiment Set Up Schematic Diagram

1.4.2 Scopes

VAHT typically consists of three different parts which are turbine, gear box and generator. However, this project only focuses on turbine section. The scope for 1st objective is to validate the function of the VAHT. The basic function of turbine that has to require is the ability to rotate when water flows through the turbine. In this experiment, the 3 blades turbine and 4 blades turbine will be exposed to different water flow speed and determine its minimum water flow speed required. To achieve the objectives, the water flow condition must be in turbulence condition. The turbulence intensity must be at least higher than 10% to obtain high turbulence flow. The experiment data that will be obtained are

- Angular speed versus azimuth angle for 3 blades and 4 blades
- Tip speed ratio (TSR) versus time for 3 blades and 4 blades

Next, the scope for 2nd objective is the parametric study of the VAHT under realistic stream condition. There are two parameters that will be focused on this research, which is the number of blades and pitching angle. The turbine will change its number of blades (3 and 4 blades) and change its pitching angle (-2, 0 and +2). The effect of the turbine design parameter to the performance of the turbine is the outcome in order to achieve the 2nd objective. The result that is expected to obtain from the experiment is the rotational speed of the turbine under different number of blades at the water flow speed of 0.45m/s. Furthermore, the water flow turbulence intensity must higher than 10% to have high turbulence flow. Similarly, another result that will be obtained is the rotational speed of the turbine under different pitching angle at flow speed of 0.68m/s. The reason for these two experiment having a different water flow speed is because toe-in pitch angle require a higher water flow speed to rotate. The experiment data that will be obtained are

- Comparison for 3 blades and 4 blades to the tip speed ratio (TSR)
- Average angular speed versus water flow speed for 3 blades and 4 blades
- TSR versus time for different pitching angle (-2, 0 and +2)

Lastly, the scope for 3rd objective is to quantify and qualify the data of self-starting characteristic of VAHT. The angular speed versus azimuth angle will be plotted out to identify the azimuth angle that provides positive torque and negative torque. For further understanding of the characteristics, the trend of the turbine from stagnant condition to steady rotational condition will be plotted out. This is to understand behaviour of the turbine when it starts to rotate. On the other hand, flow visualization for the flow pattern of the blade will be taken. The blade will be varried from 0 to 360 degree of azimuth angle in the increment of 45 degrees. Moreover, the flow pattern from upstream to downstream will be visualized as well. The experiment data that will obtained are

- Flow pattern for 1 blade at every 45 degrees of azimuth angle.
- Flow pattern from upstream to downstream.

1.5 Thesis Outline

Chapter 2 of thesis contains critical review of literature related to Vertical Axis Hydrokinetic Turbine. There are several sub chapter will be discussed in this chapter 2, which is overview of VAHT, theory of VAHT, performance study of VAHT and previous study. First, the types of hydrokinetic turbine and the geometry of VAHT will be discussed in the first sub chapter. Next, the theory of VAHT sub chapter will discuss the background theory and related equation of vertical axis turbine. The factor and the theory on the low self-starting characteristic, the effect of different pitching angle and different number of blade to turbine performance will be discussed in the performance study section. Lastly, previous study on VAHT from previous researchers will be briefly discussed in the last section of this chapter.

Chapter 3 presents an overview of the experimental apparatus and the device that will be used to conduct the experiment. Besides that, the experiment procedure will be discussed in detail in chapter 3. The challenges and method of turbine design and experiment set up will discuss in Chapter 3. Next, the experiment procedure will be discussed in detail too. Lastly, the instrument that involved in the experiment will be shown in the last section of this chapter.

Chapter 4 presents a complete of results and analyses of the project along with the corresponding discussion. The angular speed for different blade profiling and different number of blades will be presented in this chapter too. Afterward, the flow visualization result will be discussed in detail too. The dynamic flow behavior will be presented.

In the end, the conclusion and recommendations for future are presented in chapter 5. In this chapter, a summary of all the work and result will be shown in this chapter. Lastly, recommendation and limitation of the project will be discussed.

CHAPTER 2

BACKGROUND

This chapter presents background study and theory related to VAHT. There is subsection will be divided in this chapter. Specifically, overview of VAHT, theory of VAHT, performance study of VAHT, facilities and previous study. At first, overview subsection will consist of types of hydrokinetic turbine that available in the market. The pros and cons of each type will be discussed. In addition, the geometry and the basic principle of VAHT will be explained in overview subsection to understand how VAHT works. Next, performance study of VAHT will include the effect of pitching angle and number of blades to the performance of the VAHT, Furthermore, low self-starting characteristic of VAHT will be discussed detail in this subsection as well. Lastly, previous study from other researchers will be presented in the last section of this chapter. The approach and scope of their study will be included in the last subsection.

2.1 Overview of VAHT

There are two basic types of hydrokinetic turbine, which is vertical axis(VAHT) and horizontal axis(HAHT). Both types of hydrokinetic turbine have its own pros and cons(Khan *et al*., 2009, Güney and Kaygusuz, 2010). Hydrokinetic turbine separates to two categories based on the axis of turbine rotor alignment with respect water flow direction. Two categories which are horizontal (axial) and vertical axis (cross flow) turbine. The classification of the types of turbine as shown in figure 2.1. When the rotor axis is parallel to the water flow, that turbine is under horizontal axis turbine and these have propeller type rotor. While vertical axis turbine water is perpendicular to the rotor axis and this turbine mostly have cylindrical rotating structure. The most advantage of

VAHT is the Omni direction characteristic. Omni direction means that the turbine able to operate at any incoming water stream direction unlike HAHT only able to operate when the water stream direction is aligned with the rotational axis. Thus, this thesis will focus on study of vertical axis instead of horizontal axis, although horizontal axis has a higher efficiency.

There are two types of vertical axis hydrokinetic turbine which is Savonius and Darrieus turbine. Savonius turbine is a drag type vertical axis turbine. The working principle of Savonius turbine is based on the drag force of the blade. On the other hand, Darrieus turbine is lifted type vertical axis turbine and its rotation is based on the lift force of the blade. In comparison of this two types of turbine, Darrieus turbine has a better efficiency than Savonius turbine. Hence vertical axis turbine that selected for this project is Darrieus Turbine.

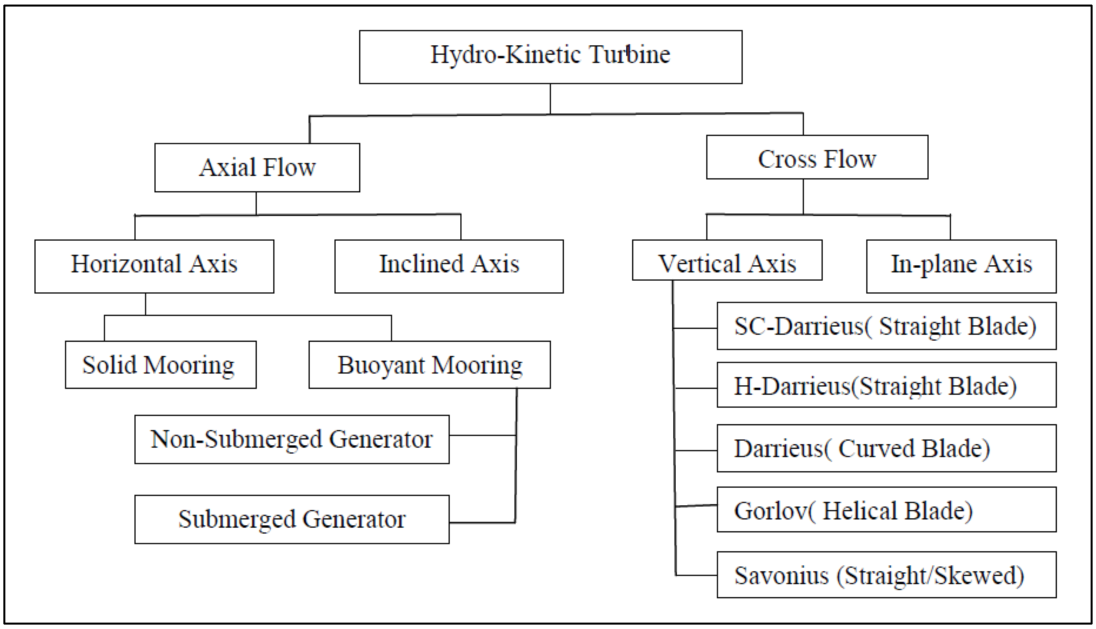

Figure 2.1 Classification of Hydrokinetic Turbine (Kaur, 2016).

Table 2-1 Advantages and Disadvantages of different type of hydrokinetic turbine.(Güney and Kaygusuz, 2010).

Type of turbine	Advantages	Disadvantages
Horizontal Axis	1) Higher Performance 2) Ease of control 3) High knowledgebase	1. Underwater generator installation. 2. Underwater cabling
Vertical Axis	1. Omni-direction 2. Generator coupling (Generator above water surface) 3. Design simplicity 4. Flotation and augmentation equipment 5. Less noise emission	1) Lower efficiency 2) Low starting torque 3) Torque ripple

VAHT for this project is a lift driven type turbine. The blade of the turbine is made of airfoil. When a stream velocity passing through an airfoil, there will be a pressure difference between upper and lower of the aerofoil. The pressure difference on the blade therefore produces lift force to the turbine. The lift force then provides a positive torque to rotate the turbine.

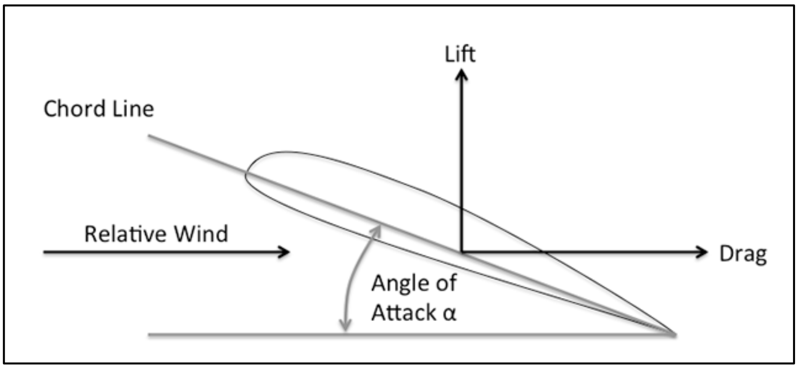

Figure 2.2 Airfoil Working Principles

Figure 2.3 shows the basic geometry of VAHT from top view. In this case, the blade will be assume to rotate anticlockwise, so the azimuth angle is angle of the blade from top view. 0 degree of azimuth angle will start at the upper part of the circle and rotate in anticlockwise. There are two velocities that the blade will experience, which is the water stream flow velocity and the blade rotational velocity. Hence, this two velocities will sum up to the resultant velocity. In the figure 2.3, resultant velocity is shown as blue arrow. The angle between the resultant velocity and the axis of airfoil is the angle of attack of the airfoil. So, the angle of attack, α will keep on changes during a full revolution. Next, when we look up to the top left of the figure 2.3, the red curve represents the pitching angle of the blade. When the leading edge of the airfoil is tilted outward of the circle axis, the axis of the airfoil will changes. Thus, the angle between the tangential axis of the circle and axis of the airfoil is pitching angle.

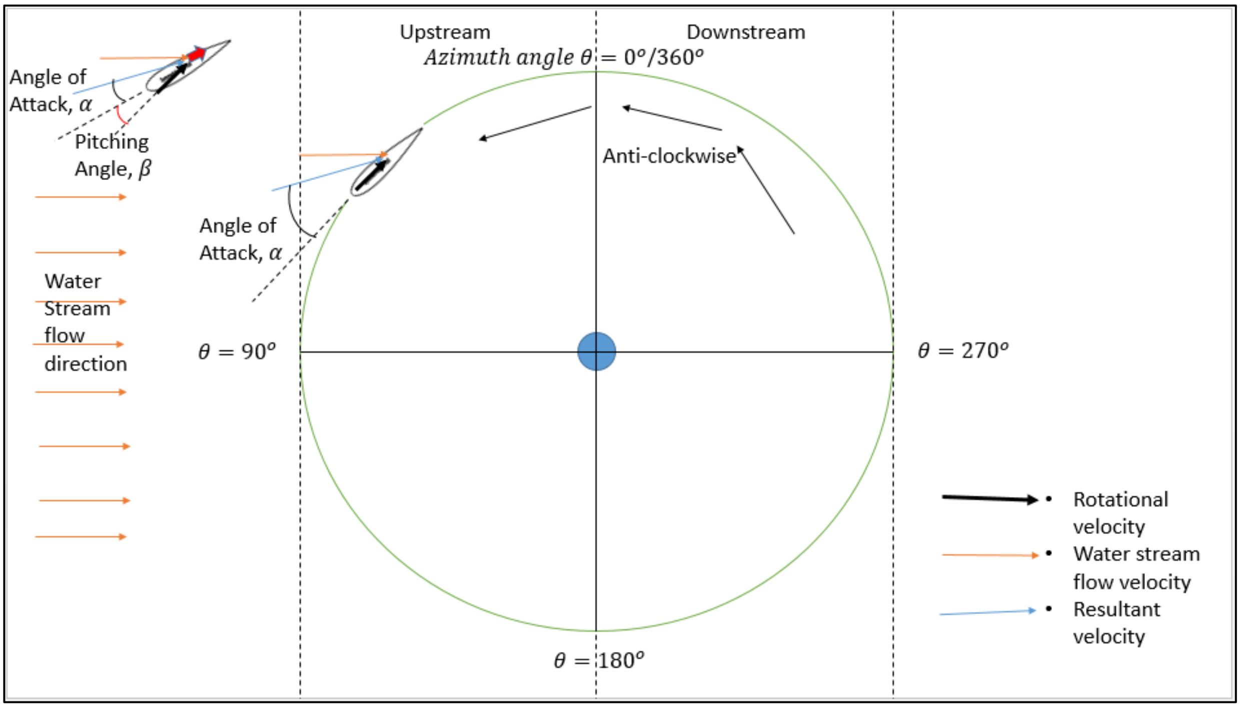

Figure 2.3 VAHT Geometry Diagram from Top View

2.2 Theory of VAHT

In 2016, Kaur has discussed the theory on how to design a darrieus VAHT (Kaur, 2016). Power coefficient C_p is the ratio output power to input power. For hydrokinetic turbine, the maximum power coefficient is 0.59 which is known as the Beltz limit(Kaur, 2016). However, a small-scale turbine has lower power coefficient due to losses and the value will around 0.25. Similar with wind turbine concept, the input or available power is depend on velocity, density, cross sectional area and power coefficient.

$$P_{in} = 0.5 \times A \times \rho \times V^3 \times C_p \tag{1}$$

Where A is turbine area (m^2), ρ is density (1000kg/m^3) , V is the water velocity and $C_p$is the power coefficient.

Tips Speed Ratio is an index for rotor's rotational speed. It can be defined as the ratio between the tangential speed at blade tip and the actual water stream speed. Power coefficient depends on tip speed ratio and the formula of tip speed ratio is shown as below.

$$TSR = \frac{Tangetial\ speed\ at\ blade\ tip}{Actual\ water\ stream\ speed} = \frac{R.\omega}{V} \tag{2}$$

where R is rotor radius(m), ω is angular speed (rad/s).

The blade of VAHT will experience two types of velocity which is water stream flow velocity and angular speed of the blade. Resultant velocity is the result of combination of water flow velocity and angular speed/ The resultant velocity will keep varies through one full rotation. Figure 2.4 below shows the relative velocity of the blade after a certain degree of rotation.

$$V_r = \sqrt{V^2 + \omega^2 r^2 + 2V\omega r\cos(\theta)} \tag{3}$$

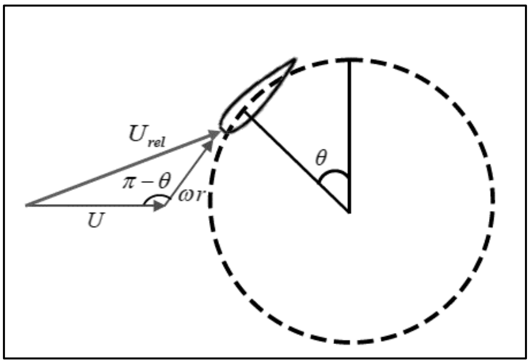

Figure 2.4 Relative angle between the rotational speed and the flow speed after θ° rotation

Solidfy σ, is the ratio between the total blade area and the projected turbine area. For self-starting turbine, the solidity have to more than 0.4 as explained Cooper (Cooper, 2010).

$$\sigma = \frac{N.c}{R} \tag{4}$$

where N is the number blades, c is the blade chord length(m) and R is the rotor radius (m).

Reynold number of the blade can be determined by using resultant water velocity.

$$Re_b = \frac{V_r.c}{K_v} \tag{5}$$

where $Re_b$is the blade Reynold number, V_r is the resultant water velocity (m/s) and $K_v$is kinematic viscosity.

The equation of angle of attack of the blade as shown at equation 6 and 7. Right half mean when the blade is at right half side when looking on top of the rotor blade (upstream). Angle of attack of the blade is the angle between the resultant velocity and the blade chord line. By assuming there is no losses in fluid momentum, the angle of attack is varied along the azimuth angle and the equation can be found below. In the equation, the angle of attack is depending on the resultant velocity or the tip speed ratio (TSR). Below figure 2.5 is the graph to show the angle of attack varied along the azimuth angle under different tip speed ratio. As the TSR increased, the maximum angle of attack experienced by the blade will be smaller. This show that the faster the turbine rotates, the angle of attack that experienced will be smaller.

$$\alpha_{righthalf} = \tan^{-1}(\frac{V_r \cos\theta}{\omega R + V\sin\theta}) \tag{6}$$

$$\alpha_{lefthalf} = \tan^{-1}\left(\frac{V_r \cos\theta}{\omega R - V\sin\theta}\right) \tag{7}$$

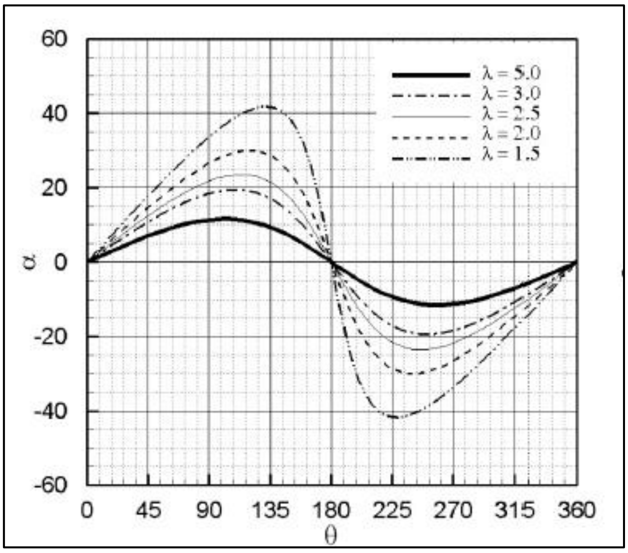

Figure 2.5 Angle of Attack as a Function of The Tip Speed Ratio and Azimuth Angle

For VAHT blades will experience the two component of forces: the drag force and lift force. These two forces will resultant a net force to two axis which is tangential and normal forces. Lift force will acting perpendicular to the resultant velocity while drag force will act in the resultant velocity direction. Once Reynolds number and angle of attack are found, lift and drag coefficient can be determined by using double interpolation (one interpolation for the Reynolds number and another will be interpolation for angle of attack). Lift and drag coefficient can use to calculate the normal and tangential coefficients. Normal coefficient is the force coefficient which is perpendicular to the axis of airfoil and toward the center of the circle. While tangential coefficient is the force coefficient that parallels to the axis of airfoil. Figure 2.6 show the schematic view of forces acting on the blade.

$$Cn = Cl \cos \alpha + Cd \sin \alpha \tag{8}$$

$$Ct = Cl \sin \alpha - Cd \cos \alpha \tag{9}$$

Where Cn is normal coefficient, Ct is tangential coefficient, Cl is lift coefficient, Cd is drag coefficient and α is angle of attack.

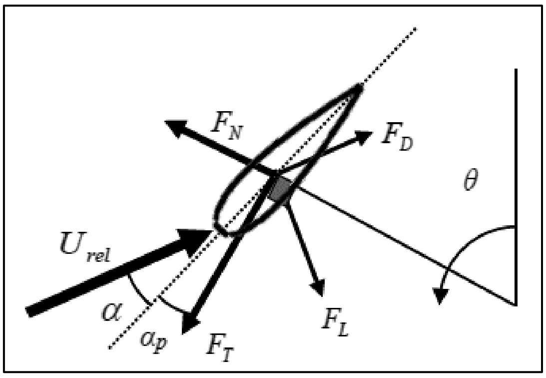

Figure 2.6 Schematic view of forces acting on a blade at the aerodynamic center of the blade

Torque comes from tangential force. Torque is the force that rotates the VAHT. Torque force will present as equation below.

$$T = \frac{1}{2} \times \rho \times A \times R \times \left({V_1}^2 - {V_2}^2\right) \tag{10}$$

Where ρ is the density of water, A is turbine swept area, R is the radius of the turbine, V_1 is the water stream velocity before the turbine and V_2 is the water stream velocity after the turbine (Kaur, 2016).

Angular speed is the rotational speed of the turbine. Angular speed of the turbine present as equation below.

$$\omega = \frac{(2 \times \pi \times n)}{60} \tag{11}$$

Where n is the revolution per minute of the turbine.

Power output is the power of turbine that able to extract from water stream to its rotational motion. Power output of the turbine is the product of torque and angular speed. The equation as shown below.

$$P_{out} = T \times \omega \tag{12}$$

Where T is the torque force and ω is the angular speed of the turbine rotor.

In the calculation, power coefficient is the important parameter that has to be determined. The higher power coefficient shows that the efficiency of the turbine is higher. As mention at above section, power coefficient for the hydrokinetic turbine will have a Beltz limit which is 0.59.

$$C_p = \frac{P_{out}}{P_{in}} \tag{13}$$

Javier Castillo mention that Vertical Axis Hydrokinetic Turbine rotational axis is perpendicular to water stream direction (Castilo, 2011). The rotation direction depends on the direction of the leading edge of the turbine blade respect with the flow. Figure 2.7 will show how the turbine rotate when water stream pass through it with aerodynamic force theory. For top view of vertical axis of the turbine, there will be two separate section which is upstream and downstream part. Upstream represent the front part of the turbine that first contact with water flow and the azimuth angle is from 0^0 to 180^0, While downstream section is from 180^0 to 360^0. Refer to figure 2.7, The black, blue and orange arrow represents rotational velocity, water stream velocity, and resultant velocity. This implies that turbine will have a resultant velocity and that velocity will cause the blade having a lift and drag force. The green bold arrow represents lift force that promotes positive torque while red bold arrow represents the drag that blade experienced.

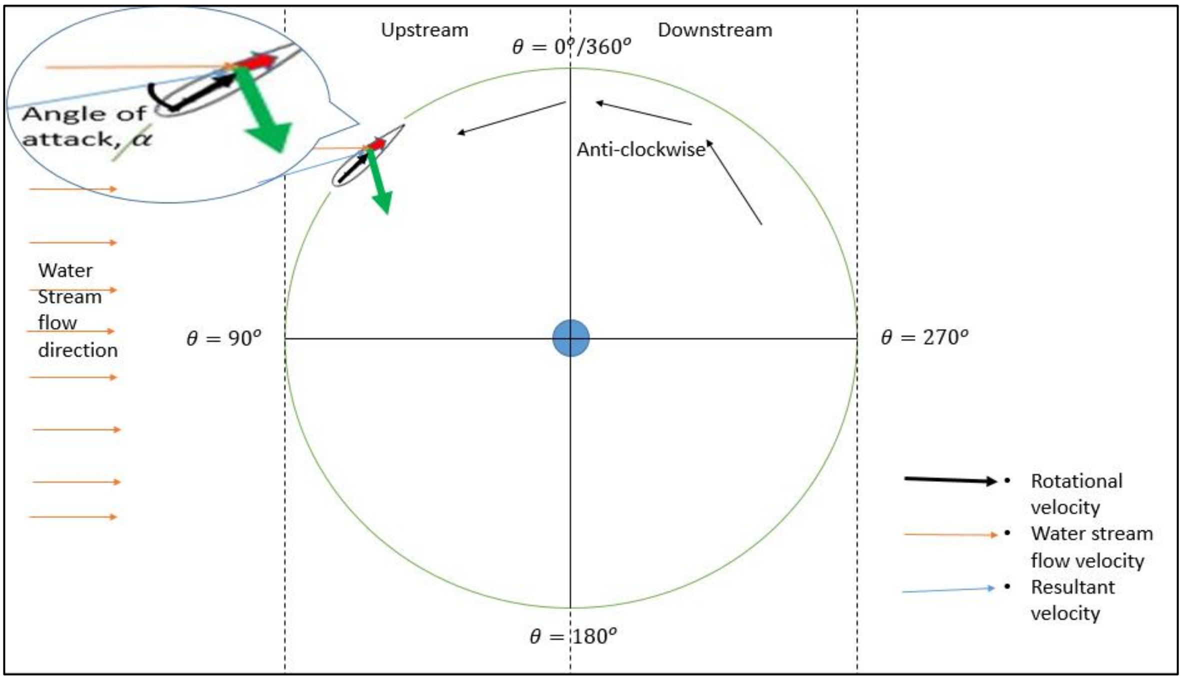

Figure 2.7 Definition of velocities and angles of VAHT from top view

2.3 Performance Study of VAHT

2.3.1 Low Self-Starting Characteristic

Complicated aerodynamic behaviour makes Vertical Axis Darrieus Hydrokinetic Turbine has a lower performance with horizontal axis turbine. During a revolution, Vertical Darrieus Turbine will have changes in blade angle of attack and Reynold's number. This complex situation that causing VAHT has a low self-starting issue. For any airfoil to generate a useful lift force, the angle of attack of the airfoil has to smaller than airfoil stalling angle. Mostly airfoil will have a low stalling angle and roughly will stall when the angle of attack is larger than 20^o. As shown as previous section, the blade angle of attack is measured between the resultant velocity and chord line for a rotating blade.

Figure 2.8 presents the blade angle of attack under different tip speed ratio (TSR). The red curve represents the angle of attack experienced by the blade. The first condition is the turbine is about to start rotate (rotating speed is slower than water stream velocity), the angle of attack experienced by the blade will be much bigger than stalling angle and thus dynamic stall will occur. When the angle of attack exceeds stalling angle, dynamic stall will occur. First the onset of the separation is postponed due to the reduction in adverse pressure gradients. In second stage, the flow will separate and a vortex is formed near to leading edge of the blades. The vortex is then convected to downstream of the blade in stage 3. When the vortex starts to leave from leading edge of the blade, this will cause sudden of loss of lift. This situation causing the VAHT having a low self-starting issue.

The second condition is the turbine having a steady rotating condition (rotating speed is faster or same with the water stream velocity), the angle of attack experienced by the blade will be smaller than stalling angle and thus produce a useful lift which promotes positive torque force. Mohamed presents this basic factor that causing vertical axis turbine having a low self-starting characteristic (Mohamed *et al*., 2017)

Besides, there are three stages for the VAHT will be experienced during the starting period. The first stage is starting from the stagnant condition up to TSR=1, where the turbine passes its critical region. Critical region is the region that VAHT struggling to rotate by overcoming the negative torque. Along 360-degree azimuth angle, there is some region that part provide negative torque and some region that provide positive torque. If the resultant torque is negative will result as the turbine cannot self-start rotate. The second stage is the turbine rotational speed speeding up to its highest peak state after it passing the critical region. Last, the third stage is the acceleration of the turbine will decrease until its reach its steady-periodic condition. The stage the turbine cannot self-start is belonged to stage 1. Once the turbine passes through the critical region, then the turbine can rotate and generate electricity.

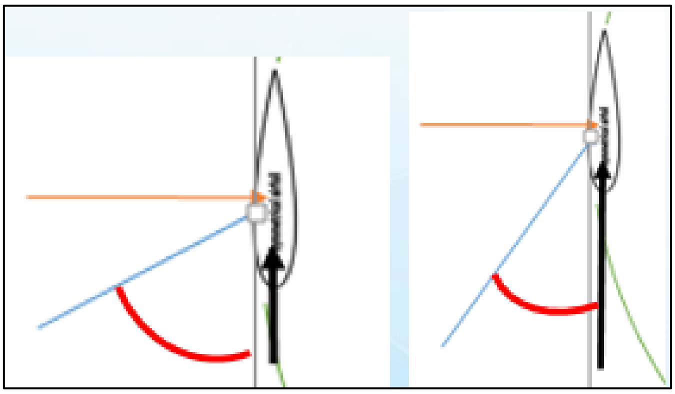

Figure 2.8 Blade condition 1 (left) and blade condition 2 (right)