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Aerodynamic Performances of Small Scale Horizontal Axis Wind Turbine Blades for Applications in Malaysia

S.A.H. Roslan, Z. A. Rasid, H.T. Toh, M.Z. Hassan

Abstract**:** ***Wind energy is one of the most viable options for clean and sustainable energy production. In Malaysia where wind source has been considered scarce, the capacity of installed wind energy production is very low. However, studies have shown that it is worthwhile to produce wind energy at several potential sites in this country. For this purpose, it is crucial that the designed turbine blade gives the highest possible blade power efficiency while structure wise, the turbine blade need to be effective in terms of avoiding possible failures. The maximum power efficiency means the blade does not only provide profile that gives maximum sliding ratio but also it must operate at the corresponding angle of attack,*** α_{max} ***that gives this ratio. At the same time, the blade must be small enough to have low weight to allow it to self-start in the low wind region. In this paper, the study is focused on the aerodynamic aspect of the design of wind turbine blade that will give the maximum power efficiency. Four factors that determine aerodynamic performance of the turbine blades are discussed: the wind condition, the airfoil profile, the blade geometry and the losses. In most of the factor, adjustments are made such that the blade operates at around the*** α_{max} ***so that the sliding ratio and thus power coefficient are maximum.***

Index Terms**:** ***Wind energy, coefficient of power, wind turbine blade, boundary element momentum (BEM) method.***

I. INTRODUCTION

Energy consumption is one of the toughest issues facing the world today. The increase in the number of population in this world as shown in **Figure 1** [1], has caused the increase in energy utilization that may result in the depletion of conventional sources of energy while increasing the emission of greenhouse gases. With the predicted usage of more than 100 million barrels per day of crude oil in 2019 [2], the shortage of oil resources in the future is strongly expected. Furthermore, in the year of 2050, the emissions of greenhouse gasses from energy sector are expected to increase by 150% compared to the level for the year of 2005, according to the IEA's energy technology perspective [3]. **Figure 2** shows the increase in the greenhouse gasses that were emitted prior to the year of 2010.

In addressing this issue, the demand for the renewable energy including the wind and solar energy has been seen to increase greatly. Compared to solar energy that depends on the present of sun during daylight, wind energy can be generated 24 hours a day and thus produce more overall energy while providing much less pollutions. Wind energy, with the revolution of wind turbine technology, is predicted to contribute 5% of the total energy of the world in the year of 2020 [4].

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* Correspondence Author

A.H.M.Roslan, MJIIT UTM, Kuala Lumpur, Malaysia.
Z.A. Rasid, MJIIT UTM, Kuala Lumpur, Malaysia.
H.T. Toh, MJIIT UTM, Kuala Lumpur, Malaysia.
M.Z.Hassan, Razak Faculty, UTM, Kuala Lumpur, Malaysia.

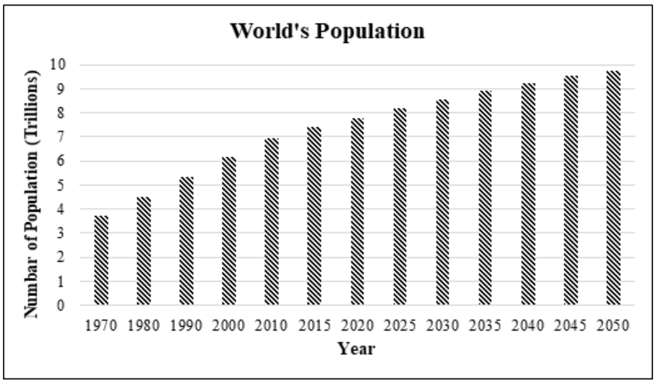


Fig. 1 The increase in the world population [1]

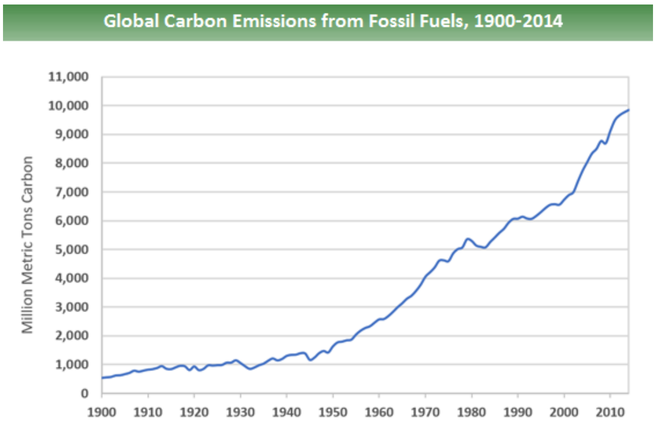


Fig. 2 The increase in the greenhouse gasses [3]

Malaysia is geographically located in 1°22' latitude and 103°55' E longitude of Southeast Asia. The weather in Malaysia gives quite a strong wind blowing during the Northeast and Southwest monsoon in between October and March, and May and September every year, respectively. With this, the weather is still characterized by having light winds and with the prevailing monotonous weather, there is a common believe that the country cannot harness the wind for feasible energy production.

Nonetheless, there have been efforts to utilize the benefits of wind energy in Malaysia such as in in 2005 where the government installed a wind turbine at Terumbu Karang resort island and in the joint venture project between the State Government of Terengganu and the largest energy provider company, TNB in 2007 where a solar-diesel-wind hybrid power plant project with combined capacity of 650 kW was developed [5]. The later project which is shown in **Figure 3** was able to reduce power generation costs on the island by almost 40%. Mekhilef et al. [5] conducted a feasibility study on several possible offshore wind turbine sites where the sites have high wind speed during monsoon seasons. It was shown that several sites in the East peninsular coast showed great potential for producing wind power energy provided that the government plays its roles by providing friendly energy policy.

Fig. 3 The Solar-diesel-wind hybrid power plant[5]

A study by Ho [6] indicated that based on global wind energy development, successful installation of wind power capacity depends very much on robust regulatory support and strong political will, something that Malaysia is still lacking and uncertain since supports are mainly given to fossil fuel energy. In a recent study by Nor et al. [7] applying a numerical weather prediction (NWP) prospecting tool for mesoscale winds shows that there is an actual potential of wind energy in Malaysia, manifested through the several economically viable wind turbine generating sites such as shown in **Figure 4**. Furthermore, it was concluded that even though solar energy and hydropower provide the highest potential renewable energy in Malaysia, the wind energy can still be a good alternative source of generating energy, especially on remote islands or in the East coastal states [8].

It is clear now that wind energy can be harnessed in this country and what is needed here is the applications of small and micro scale wind turbine as this requires smaller investments. Note that the classification of wind turbine in term of its size is as given in Table 1 [9] where SC is small scaled and S, M and L stand for small, medium and large.

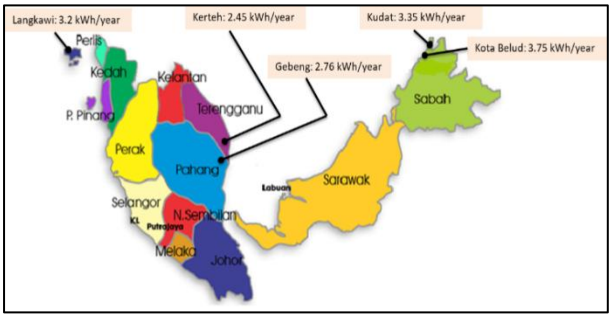


Fig. 4Possible wind sites in Malaysia [8]

Table 1   Classification of HAWT [9]

Category	Rotor dia. (m)	Swept area (m^2)	Std. power (kW)
SC-Micro	0.5-1.25	0.2-1.2	0.004- 0.25
SC-Small	1.25 - 3	1.2-7.1	0.25-1.4
SC-Household	3 - 10	7-79	1.4-16
S-Commercial	10 - 20	79-314	25-100
M-Commercial	20 - 50	314-1963	100-1000
L-Commercial	50 - 100	1963-7854	1000 - 3000

The small scale wind turbines are meant for off grid applications such as individual homes, communities or users with no access to the electricity grid in isolated areas. The design of these turbine is relatively simple with several features in the large wind turbines are avoided such that lower installation cost is required. Furthermore, in low wind speed area, smaller size turbine is practical as this allows the turbine to self-rotate. The low power supply can be augmented by using several numbers of these turbine in addition to adding other forms of power generators such as solar power generator. This can result in being a reliable energy source and socio-economically valuable amount of wind energy. It is also justifiable to focus on small and small scale wind turbine as the world's trend nowadays is moving from large size to smaller size wind turbines [9]. Barriers for large turbines are such as the availability of large scale on-shore wind farm sites, the negative impact of grid power quality, low public acceptability and losses in transmission and distribution of electricity to the consumers [10]. In addition, it was shown that large wind farms may cause significant climate change especially in terms of temperature increased [11] and escalate rate of precipitation [12,13]. And as such large scale wind turbines are as such not sustainable for long term energy production [9].

What important is the design of the wind turbine for Malaysia's applications must provide the best in three aspects: the highest aerodynamic efficiency, the most effective wind turbine structure and the good self-starting capability. Several review papers have been published [9, 10, 12-13] but in this review paper, focus is given to the first aspect i.e. improving the aerodynamic performance of small scaled wind turbines that are suitable for the country of Malaysia.

II. BASIC AERODYNAMIC PERFORMANCEs

The basic aerodynamic performance of a horizontal axis wind turbine (HAWT) is given in this section after the difference between HAWT and vertical axis wind turbine (VAWT) are given.

A. HAWT vs VAWT

Wind turbines can be categorised into two types based on the rotational axis of the rotor: Vertical axis wind turbine (VAWT) and horizontal axis wind turbine (HAWT) are such as shown in **Figure 5**. Even with many weaknesses, the VAWT is still being developed due to having special attributes such as its generator equipment that can be put on the ground [14]. The HAWT however, has been shown to be the superior machine tool in extracting energy from wind, and is characterized by higher energy efficiency, less sensitiveness to off-design conditions, low cut-in wind speed and more mechanical stability compared to the VAWT [15].The HAWT consists of a rotor, generator, gearbox and degree of freedom control systems such as controlling pitch, yaw and tilt while the rotor consists of blade, hub and shaft where the blade is the key element of wind turbines that converts wind energy into mechanical energy.

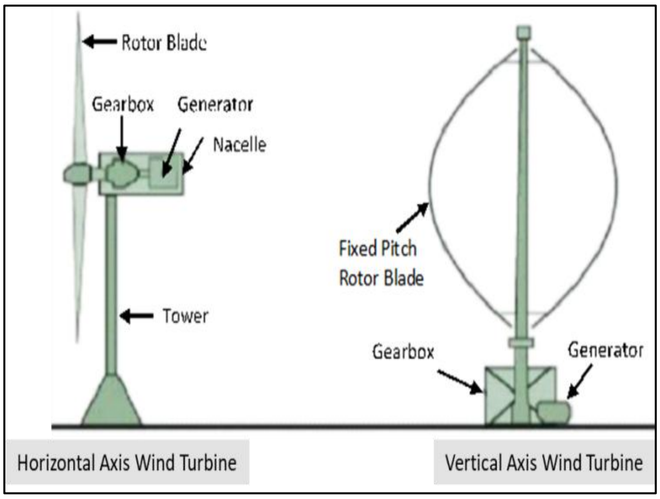


Fig. 5 The HAWT and the VAWT

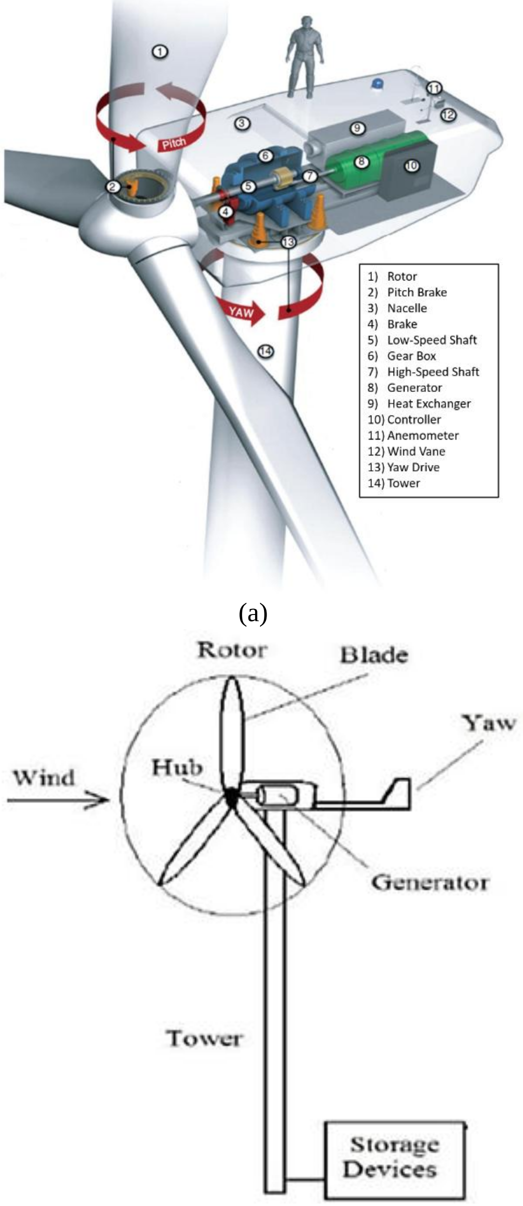
B. The Principle Operation of Small HAWT

The way a small-scaled HAWT operates is no different than the way the larger one does. The difference between the two is the simplicity that the small-scaled HAWT has without having some of the control systems such as shown in **Figure 6**. The operation of a HAWT is about tapping power from wind as much and as efficient as possible without damaging the turbine itself. The theory on the aerodynamic operation of wind turbine is well documented in literatures and is simplified here for completion purpose. Theoretically, with reference to **Figure 6**, the amount of energy provided by the wind is estimated by the kinetic energy formula,

$$P_w = \frac{1}{2}\rho A V^3 \qquad (1)$$

where P_w is the power generated by wind, ρ is the air density, A is the swept area of the blade and $V$is the wind velocity. Here with ρ and V are as provided by the wind, P_w can only be increased with higher A. Unfortunately, too high A means too high an inertia and too big a size of a turbine blade which may affect the self-starting capability of the turbine for low wind regions like in Malaysia. Beyond this, the amount of mechanical energy that can be tapped from this wind energy depends on the turbine aerodynamic efficiency, C_p. The actual amount of energy, P is

$$P = C_p P_w \qquad (2)$$



(a)

(b)

Fig. 6 The components of a) a large HAWT and b) a small scaled HAWT [11]

Regardless of the turbine size, the maximum C_p can be obtained, as derived by Benz is C_p= 0.593 since the nature of the amount of energy that can be tapped depends on the amount of wind speed reduction in the energy conversion process as the energy approaches the blade. C_p can further be reduced by wake rotation, low lift force and high drag force, tip loss and other minor losses, to be addressed later.

While for a large turbine, somewhat lower C_p can be made up by optimal source of high speed wind but for small scale and micro turbines operating in low wind speed region, it is critical to maximize the value of C_p.

The possibility of producing mechanical power, P from wind comes from the aerodynamic behaviour of the turbine blade's aerofoil. The airfoil geometry i.e. the cross-section of the blade is given in **Figure 7**. It shows the shape of the airfoil that causes the top-down pressure variation with lower pressure area at the top of the airfoil as the wind blows toward it and as a result, lift force, F_L is produced. Consequently, the blade rotates at angular velocity, ω. With the wind speed, V coming in the direction perpendicular to the plane of rotation and air also move at $r\Omega$ due to the movement of the blade but in opposite direction to the blade movement, we have a relative velocity of the wind, v_{rel} making an angle α about the airfoil cord length. The angle α is called the angle of attack. The rotation of the blade about the axis of rotation provides speed and torque to the rotor and thus mechanical power to the wind turbine that is later to be converted to electrical power.

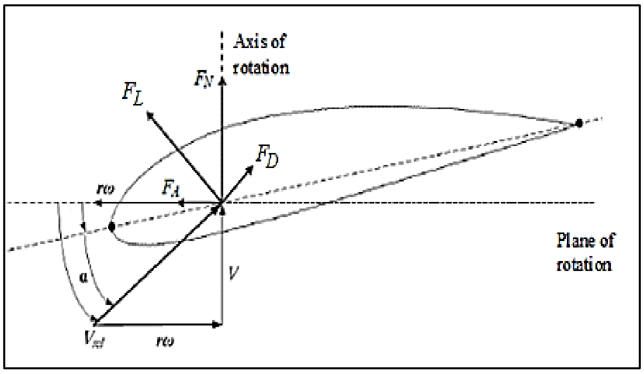


Fig.7Forces and velocities on an airfoil

Beside the lift force, there is resistance as well in the form of drag force, F_D that occurs in the direction opposite to the direction of the v_{rel}. Furthermore, coefficient of lift, C_L and drag, C_D were introduced as a mean to rate the lift and drag forces with respect to air condition such as

$$C_L = \frac{F_L/_A}{\frac{1}{2}\rho V^2} \tag{3}$$

$$C_D = \frac{F_D/_A}{\frac{1}{2}\rho V^2} \tag{4}$$

Thus, it is important to notice the amount of F_L and F_D and the sliding ratio, C_L/C_D are associated to the airfoil shape and the wind condition. While the main wind characteristic is its speed, the wind condition can be represented in Reynold's number, Re such that

$$Re = \frac{v_{rel}C}{\upsilon} \tag{5}$$

where the dynamic viscosity of air is υ = 1.511 x 10-5 at 20° C. As such, the C_L, C_D and the sliding ratio are always associated with the Re. For maximum power efficiency, the values of C_L should be high while C_D should be low and thus for maximum efficiency and power, C_L/C_D ratio should be at its highest value and for each aerofoil, this only occurs at a certain angle of attack, ω_{max}. Furthermore, because of low wind speed in Malaysia and the application of the small-scale wind turbine, it is expected the low Re of about 100,000 is to be used in this study. At low Re, the turbine blade is designed to be less complicated to reduce installation cost as mentioned before and as such many control systems are neglected.

The C_L, C_D and the sliding ratio, C_L/C_D can be predicted using analytical, numerical and experimental methods. Experimentally, the measurement is made in wind tunnel as has been done for aerofoil used in aeroplane industries. In recent years, several researchers have conducted studies to determine C_L and C_D using computational fluid dynamics (CFD) [16-18]. Furthermore, it can also be done through analytical method such as in XFOIL software

III. FACTORS THAT AFFECT AERODYNAMIC PERFORMANCES

Aerodynamic performance of a wind turbine is measured from the amount of torque, T, power coefficient, C_P and power, P obtained. High aerodynamic performance depends on many inter-related factors that can be categorized into 4 groups: wind conditions, airfoil design, blade geometry and loses such as shown in **Figure 8**. Specifically for small scaled turbine, high power coefficient, C_P is the main performance that we are seeking and in reaching this,high sliding ratio,C_L/C_D is the most important requirement where factors in the 4 groups above are directly or otherwise involved in improving the C_L/C_D ratio.

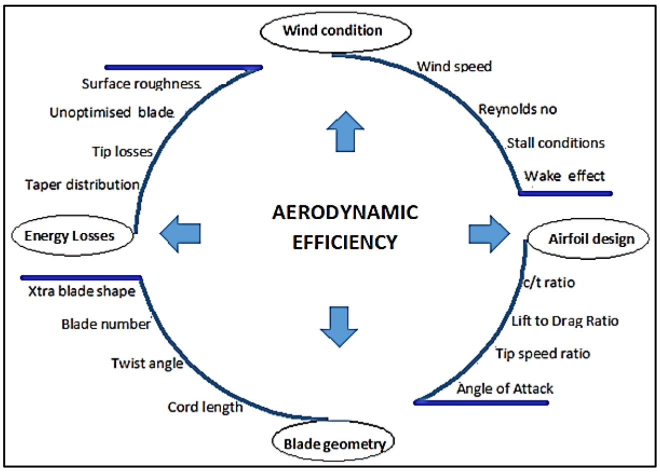


Fig. 8 Factors that affect aerodynamic performance of turbine blade

A. Wind Conditions

The higher the wind speed, the higher the theoretical wind power, P_w that can be tapped such as given in Eqn. (1). Also, as the wind speed is increased, the sliding ratio, C_L/C_D will be increased. In general, the highest sliding ratio is required to get the highest power coefficient, C_P that will ensure the highest actual power, P to be tapped. However, it should be noted that the decrease of C_D will increase the C_P but the increase of C_L may only give small contribution to the increase in torque and thus power [21]. Two important parameters that directly affect the amount C_L/C_D ratio: the angle of attack, α and the wind conditions that can be represented in the form of Re. In general, the C_L/C_D ratio increases with the increase of the angle of attack until it reaches the maximum sliding ratio that occurs at α_{max}.

Also in general, the C_L/C_D ratio increases with the increase of Re. A real concern is the reduction in the sliding ratio right after it reaches its peak in the so called stall phenomena as α is further increased beyond α_{max}. However, for small Re such as in this study, the effect of stall phenomena can be considered small [21].

Sayed et al. [16] conducted aerodynamic analysis using computational fluid dynamic (CFD) method based on the finite-volume approach in determining the plots of sliding ratio against angle of attack at several wind speeds for a number of NREL series profiles. The numerical results were shown to agree excellently with the wind tunnel measurements. It was shown that as the wind speed was increased, the sliding ratio was increased as well while the maximum sliding ratio occurs at specific angle of attack associated to the airfoil. A similar aerodynamic performance study was conducted by Nigam et al. [17] and Koç et al. [18] to determine the C_L, C_D, sliding ratio and C_P of HAWTs using the CFD method.

B. Airfoil Design

Beside the wind condition, it is the shape of the airfoil that makes possible the existence of F_L and F_D and thus affects the values of C_L, C_D and C_L/C_D ratio. Wind turbine airfoil is produced in 'families' such as NACA and NREL families but individual profiles have also been produced. An example of a NACA profile of NACA 4412 is given in **Figure 9**. While the most important criteria for a good airfoil is to give high C_L/C_D ratio which in turn will increase the C_P of the wind turbine, other requirements include having good stall characteristics, consistent performance at varying Re and good performance with regards to roughness effect [19]. The shape of the airfoil that affects the sliding ratio is characterised by its thickness, chamber and nose angle. The NACA airfoil in the 1970s and 1980s was designed in symmetrical shape that cannot handle stall, varying air's Reynold numbers and leading edge contamination that leads to energy loss [13]. With the addition of chamber later, the performance of airfoil was improved such as increasing the ratio of thickness of the blade over chamber, t/c will increase the C_L. Furthermore, increasing nose radius will increase t/c and hence will increase the C_L at the same time. High thickness is also important for avoiding structural failure.

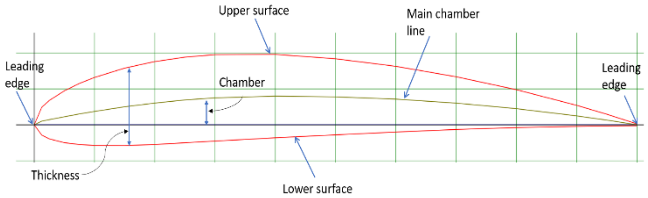


Fig. 9 The NACA 4412 airfoil

C. Blade Geometry

The wind condition and the airfoil shape determine the C_L/C_D ratio that will affect the efficiency of turbine blade. However, to get the maximum C_L/C_D ratio which occurs at α_{max}, the blade geometry is variably twisted throughout its length to capture the highest possible C_P and power [20]. This is necessary because as the blade location moves toward its tip, the air speed, $r\Omega$ is reduced as r is decreased. The NREL Phase VI, for example has 5^0 pitch angle and twist angles that varies throughout the blade span such as shown in **Figure 10**. This optimization of blade geometry can be simply done using BEM theory. Here, the optimization is based on the designed tip speed ratio, $\lambda = r\Omega/v_{rel}$ and the maximum angle of attack, α_{max} to determine the final values of chord length and the angle of twist[21]. In the case of variable wind speed, the designed tip speed ratio must be variable as well. Higher tip speed will cause the increase in efficiency while lowering the torque. As higher tip speed ratio along with increasing the number of blades require reduction in chord width that leads to narrow blade profiles and this will reduce the solidity, material required and cost of production and thus increases the self-starting capability. Furthermore, tip speed ratio of 9 to 10 for two bladed rotors and 6 to 9 for three bladed rotors have been suggested [22]. To meet all these effects, more than one airfoil should be used throughout the length of the blade [14]. In relation to this, a three bladed design is considered the best in terms of the minimum loss of efficiency and environmentally advantageous [14].

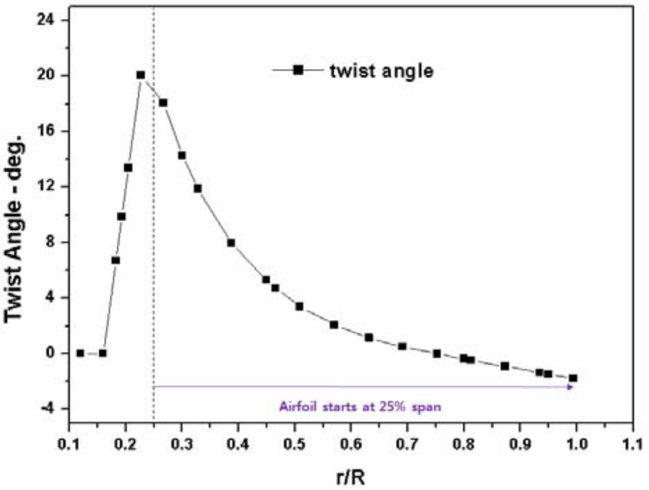


Fig. 10: The variable twist angle of the NREL Phase IV (Mo and Le)

D. Losses

At high angles of attack, the so call stall phenomena has caused flow to separate, causing the drop in F_L and the increase in F_D and as such the sliding ratio will decrease. A model proposed by Viterna and Corrigan allows the prediction of C_L/C_D in the stall region. In a related problem that is called stall delay, while having high lift coefficient in the stall region, the rotation effect of the HAWT that causes air to flow around the tip from the lower surface to the upper one which causes the reduction in F_L and power, P. This phenomenon is called tip-loss. Furthermore, poor performance of turbine may be attributed by leading edge contamination that leads to the so called roughness effect.

IV. CONCLUSIONS

The wind conditions in Malaysia has been discussed. It leads to the conclusion that wind energy can be harness in this country at several spots where small scaled wind turbines may be applied in combination with other means of energy generator.

Following this, the four factors that determine the aerodynamic performances of wind turbine are discussed. Almost all the factors are about ensuring the turbines to operate at angle of attack, α_{max} that gives the maximum sliding ratio so that the maximum C_P can be attained.

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AUTHORS PROFILE

Siti Amni Husna Roslan earned her Master's degree in Mechanical Engineering from the Universiti Teknologi Malaysia (UTM) in 2017. He has published more than 20 conference and journal papers mainly in the area of natural fibre composite. She is currently doing her doctorate in sandwich composite wind turbine. Her current areas of research are composite material, natural fibre composite and aerodynamics and wind turbine. Siti Amni Husna Roslan is a member of the Malaysian Board of Engineers.

Zainudin A. Rasid earned his PhD in Aerospace Engineering from the Universiti Putra Malaysia, Serdang in 2013. He is currently working as a senior lecturer at the UTM, Kuala Lumpur. He has published more than 50 papers in forms of journal and conference proceeding mainly in the area of buckling and vibration of composites and smart composites and CNT composites and rotordynamic of shaft. His current areas of research are the composite material, carbon-nanotube reinforced composite, green composite, smart material, stress analysis, buckling and post-buckling analysis, plasticity, numerical method and finite element method.Dr. A. Rasid is a member of the Malaysian Board of Engineers.

Toh Hoong Thiamis a senior lecturer at the Universiti Teknologi Malaysia, Kuala Lumpur.He received his PhD in Engineering Mechanics from the Virginia University, USA in 2003. His areas of interest in research are fluid mechanics, computational fluid dynamics, wind turbine and engineering design.Dr Toh has published more than 50 publications in the forms of book, book chapter, high impact journal and conference proceeding. He is currently asenior member ofthe American Institute of Aeronautics and Astronautics(AIAA)and at the same timea member of the Malaysian Board of Engineers

Mohamad Zaki Hassan earned his PhD at the University of Liverpool in 2012. He is currently working as a senior lecturer at the UTM, Kuala Lumpur. He has published more than 60 papers in forms of journal and conference proceedings mainly in the subject of composite, sandwich structure and natural fiber. He is fortunate to have studied recycling polymer that combined with low cost material for ease fabrication of the product. Kenaf, jute, hemp and bamboo are the main natural fibres that are used as composite reinforcement in this work. Dr. M Hassan is a member of the Malaysian Board of Engineers.