DESIGN AND PERFORMANCE TESTING OF A SMALL-SCALED HORIZONTAL AXIS WIND TURBINE FOR LOW WIND SPEED REGIONS

[1]YIN YIN HTAY AUNG, [2]MYAT MYAT SOE, [3]AUNG MYAT THU

[1,2,3]Department of Mechanical Engineering, Mandalay Technological University, Mandalay The Republic of the Union of Myanmar
E-mail: [1]yinyinhtayaung@gmail.com, [2]myatmyatsoe.mtu@gmail.com, [3]laymyathnar@gmail.com

Abstract- In this paper, locally developed small wind turbine was tested to observe power performance at low wind speed range of 1.5m/s to 6m/s. Thin airfoil was selected from well-known series for low Reynolds' number due to low wind speed. SG 6043 airfoil was used for low Reynolds' number 150,000 [12]. The turbine blades were fabricated from Ya-Ma-Nay wood because of its easily available, light weight, good strength, and low-cost. The design rotor swept area was 2 sq. meters and its design angle of attack was 5. Tip speed ratio was chosen 6 for three-bladed wooden wind turbine. The rotational speed of rotor was designed 500rpm at rated wind speed 6 m/s. Performance Testing was carried out on the roof of Main-Building at Mandalay Technological University, Mandalay. The wind turbine hub placed 16 m above the ground. The experimental data were measured every 15 minutes. Instantaneous cut-in wind speed occurred around 3.5 m/s and average cut-in wind speed occurred 2.5 m/s. The power versus velocity curves were shown for the turbine blades' performance.

Index Terms- Low wind speed, performance test, thin airfoil, Ya-Ma-Nay wood.

I. INTRODUCTION

Renewable energy of wind is one of the cheapest and abundant sources for providing electrical or mechanical power. It can be found everywhere and every time. But wind cannot extract required power if it hasn't sufficient and regulated strong velocity. The blowing wind possesses kinetic energy and strikes the wind turbine blades. From this action some of wind kinetic energy are lost and transmit to useful rotational or mechanical energy of wind turbine shaft. The maximum power that can be extracted is 59.3% of the power in wind [2]. Electrical energy is converted from this mechanical energy of rotating shaft by coupling with generator. Therefore, wind turbine rotor's blade is an energy converter.

Besides, the turbine blades' profile also plays an important role to capture the wind energy efficiently and effectively. At the same wind velocity, energy harness from the wind depends on direction of the airstream, blade profiles and angle of attack. According to its profile, wind flows faster at the upper surface of airfoil than the lower one. The pressure distribution around an airfoil inversely
proportional to wind velocity distribution. The pressure on the upper surface is lower than that on the underside [10].

This causes the pressure difference and creates lift force. The parasitic force which is parallel to the wind is called drag. The study of these forces is called wind turbine aerodynamics. The optimum airfoil profile is chosen from maximum lift to drag ratio at design Reynolds number and angle of attack. The optimum airfoil profile gives the good performance in power extraction from wind. That is why, the aerodynamic analysis of wind turbine blade is important in design consideration.

Fei-Bin Hsiao investigated and compered the coefficient of performance of twisted and tapered, not-tapered, and untwisted horizontal axis wind turbine (HAWT) blade geometries with the same diameter of 0.72 m using the same NACA4418 airfoil [3]. Wind tunnel testing is needed to know the blade efficiency at various range of wind speed conditions Outdoor testing confirm the wind turbine operate well at selected site location.

II. METHODOLOGY

A. Design of Wind Turbine Rotor Blade

In design consideration, available generator power and its rotational speed must be known firstly. This is important to design the direct-drive small wind turbine.

$$D = [P \times (\frac{47\lambda}{N})^3]^{1/5} \quad (1)$$

where D is the diameter of rotor(m), P is the required power output(W), λ is design tip speed ratio, N is generator rotational speed(rpm). Blade elements along the blade must be divided between 10 and 20 sections. In this design calculation, there are ten sections along the blade. Then chord length for each section can be calculated by following equation assuming that lift coefficient is approximately equal to 1.

$$c = \frac{16\pi R\left(\frac{R}{r}\right)}{9\lambda^2 B} \quad (2)$$

where c is the chord length(m), R is the radius of rotor(m), r is the radius of specific blade element (m), and B is the number of blade. Thereafter, linearization of blade chord lengths is calculated by Mathematical formula to get smooth profile along the blade.

The comparison between theoretical chord length and linearization of chord length at each element is shown in Fig. 1. In this curve, the differences are large at the root sections and nearly same at the middles and tips. A straight line drawn through the 70 percent and 90 percent span points not only simplifies the plan-form but removes a lot of materials close the root [2]. The comparison between theoretical and linear chord length shown in Fig. 1.

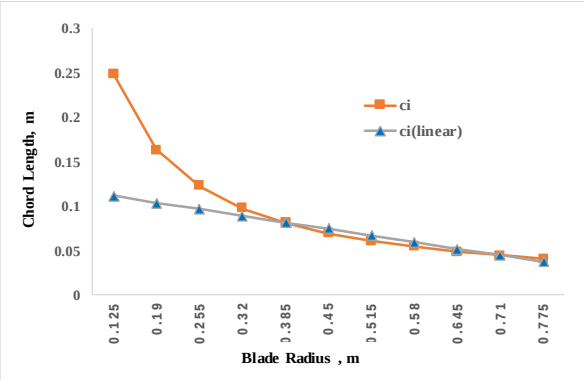


Fig. 1 Blade chord distribution along the blade

The design angle of attack(α) is chosen based on maximum lift to drag coefficient ratio at designed Reynolds' number [11].

$$\mathrm{Re} = 68500 \times c \times V_{rel} \quad (3)$$

$$V_{rel} = V \times \sqrt{(\frac{r}{R}\lambda)^2 + 1} \quad (4)$$

where Re is the Reynold's number, V_{rel} is the relative wind velocity (m/s) and V is the rated wind velocity (m/s).

Low Re airfoils suited for small wind turbine applications must be designed to avoid high leading edge suction peaks and high adverse pressure gradients that lead to flow separation. Geguere and Selig discuss the use of thin airfoil that consist of SG 60XX series of thin airfoil family (SG6040-SG6043) suited for application in small wind turbine blades operating in the Re range of $1x10^5$-$5x10^5$ [12].

The airfoil selected for this small wind turbine is SG 6043, as shown in Fig. 2.



Fig. 2 SG 6043 airfoil profile

Blade angle (β_1) is important to shape the blade.

$$\lambda_i = (\frac{r_i}{R})\lambda_d \quad (5)$$

$$\phi_i = \frac{2}{3}\tan^{-1}\frac{1}{\lambda} \quad (6)$$

$$\beta_i = \phi_i - \alpha_d \quad (7)$$

where ϕ_i is the air angle (deg), α is the design angle of attack (deg) and β is the blade angle (deg). The blade angle at each section need to be linearized like as blade chord length. The linearization of blade angle results is compared with theoretical results shown in Fig. 3.

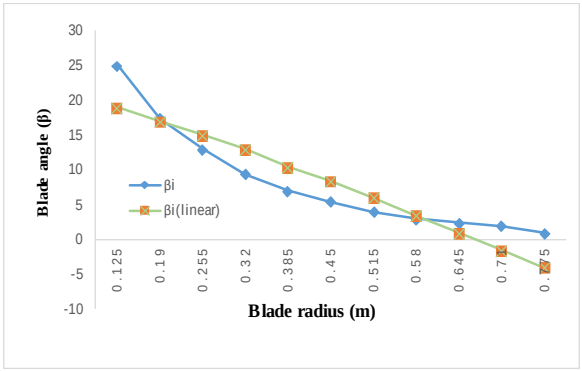


Fig. 3 Blade angle distribution along the blade

The blade profile along the blade is shown in Fig. 4. The blade setting angles (β) are placed from leading edge along the blade. Horizontal axis wind turbine needs yaw control. The yaw axis is the directional axis of a wind machine. The tail vane keep the horizontal axis wind turbine aimed into the wind. This system uses passive yaw control.

$$A_{vane} > \frac{D^2}{40} \quad (8)$$

where A_{vane} is the tail vane area.

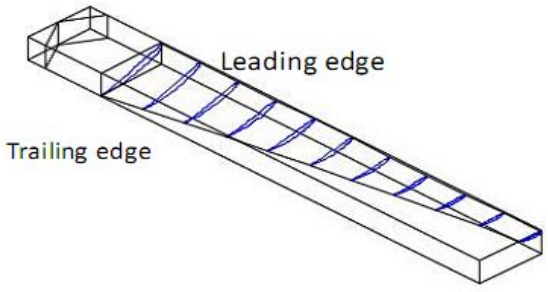


Fig. 4 Wind turbine blade with airfoil profile

TABLE I
TECHNICAL SPECIFICATIONS FOR SMALL WIND TURBINE

Name	Value	Unit
Rated Power output of Wind Turbine	50	W
Rated wind speed	6	m/s
Cut-in wind speed	2.25	m/s

Cut-out wind speed	12	m/s
Rated rotational speed	500	rpm
Cut-in rotational speed	160	rpm
Cut-out rotational speed	900	rpm
Permanent magnet generator efficiency	0.85	%

continued

Diameter of rotor	1.55	m
Diameter of hub	0.25	m
Type of airfoil	SG6043	
Width of tail vane	0.55	m
Height of tail vane	0.6	m
Tower Height	2	m

B. Implementation of Blade Design

Implementation of Blade Design The entire assembly is designed for ease in local construction in local workshops and using as many local resources as possible. The selected blade materials must have good strength, light weight, and free of knob. Ya-ma-nay wood has good strength, light weight, and low-cost in Myanmar. So turbine blade is shaving with Ya-ma-nay wood.

Blade Design is drawn by using Auto CAD 2010 and then imported to Master Cam software. Then Ya-Ma-Nay wood blocks were shaving with ANELUM milling machine to get the required shape of and turbine blades. Fig. 5 shows the gross cutting with flat endmill and Fig. 6 shows the fine cutting with sphere endmill. This action can also be done with local carpenters to reduce cost.

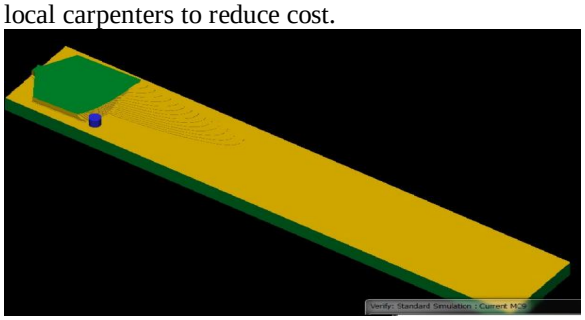


Fig. 5 Demostration of wind turbine blade rough machining

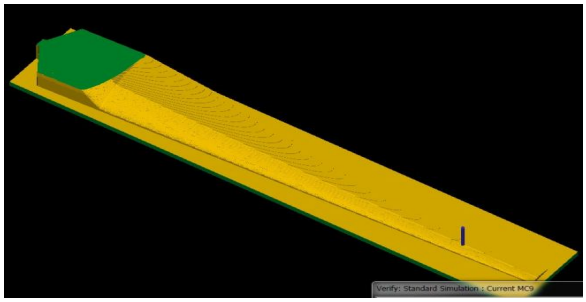


Fig. 6 Demostration of wind turbine blade fine machining

The wind turbine blades were coated with resin to resist the erosion and improve the strength of blade. And then painted to resist weather effect. At root section of the blade, holes are drilled to fix the generator shaft and assembly the three blades.

III. EXPERIMENTAL SET UP

Turbine blades rotate the shaft of permanent magnet generator which gives power of 50 W at rated rotation of 500 rpm. The available wind speed fluctuates the whole time and sometime it clams. So Battery Charging is needed to storage the electricity. Fig. 7 shows the diagram of installed three-bladed horizontal axis wind turbine. This wind turbine is tested at root slab of Mandalay Technological University Main Building. It is about 14m above the ground.



Fig. 7 Constructed three-bladed horizontal axis wind turbine

The wind rotates the rotor blades and give mechanical power. Rotor and generator are directly connected and therefore rotation of blades rotate the generator shaft and give electrical power. The layout diagram of experimental test shown in Fig. 8. Changeover is used as electrical brake. The charger changes the output power from three-phase to single-phase. The battery is charge by using charger.

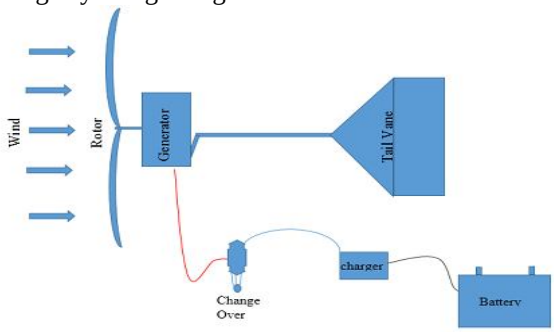


Fig. 8 Layout diagram of tested wind turbine

Wind speed is collected with hand-held anemometer and output current is measured by clamp meter. DC voltage is read by DC indicator on charger.12V 6.5 Ah battery is used for electrical storage. The measuring instruments of experimental test are shown in Fig. 9.

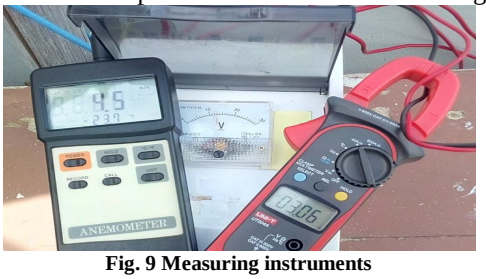


Fig. 9 Measuring instruments

Output Power(W) and coefficient of performance (C_p) are calculated by following equation.

$$P = VI \quad (9)$$

$$P_{wind} = \frac{1}{2}\rho A V^3 \quad (10)$$

$$C_p = \frac{P}{P_{wind} \times \eta_g} \quad (11)$$

IV. RESULTS AND DISCUSSIONS

The direct-drive wind turbine produces electrical power based on wind velocity and type of generator used. The designed wind turbine focuses the electrical power output of 50 W at 500 rpm and wind velocity 6 m/s. The three day's test results are shown in Fig. 10, 11, and 12.

The graphs show the power output based on average velocity for three days from 1 pm to 4:30 pm.

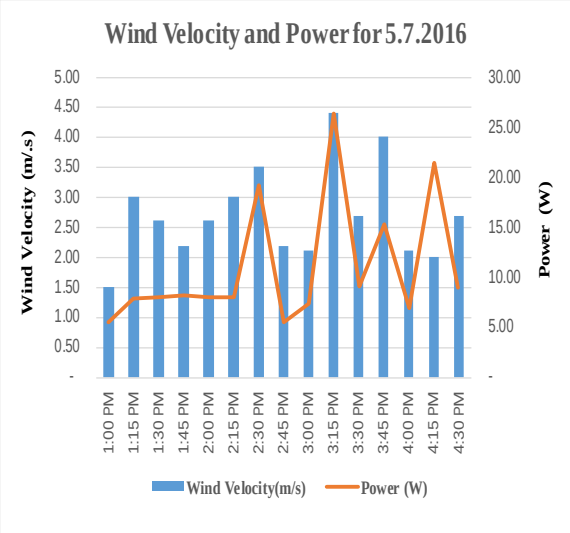


Fig. 10 Power output and wind velocity versus time for 5.7.2016

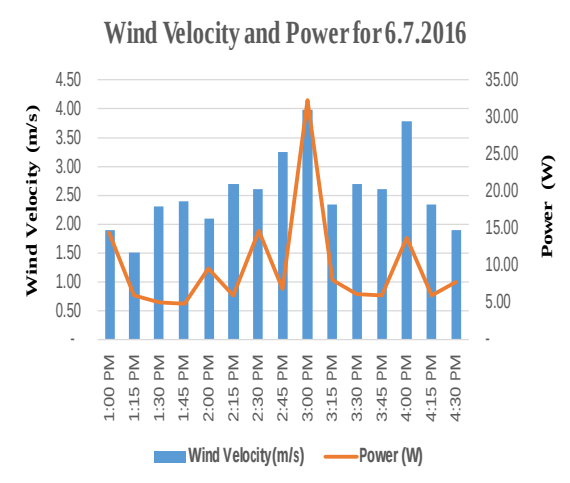


Fig. 11 Power output and wind velocity versus time for 6.7.2016

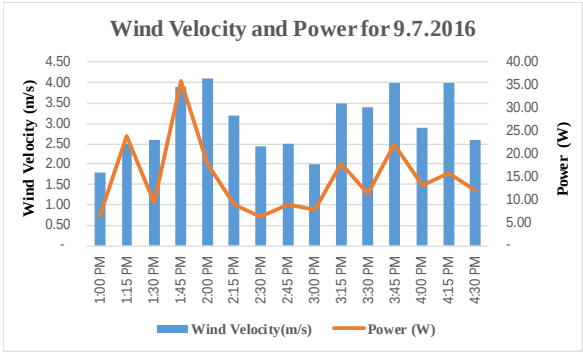


Fig. 12 Power output and wind velocity versus time for 9.7.2016

Fig. 10, 11, and 12 compare the electrical power output and average wind velocity for installed wind turbine. The average wind velocity occurs maximum value of 4m/s and minimum value of 1.5m/s. So wind turbine starts to produce electrical power at average wind velocity of 1.5m/s. But wind turbine cannot produce power if this average wind velocity blows regularly during the data collected time. The start-up wind velocity tends to increase as the time increase between 1:00 pm to 2:15 pm.

The power output of the wind turbine strongly depends on wind intensity. Although the instantaneous wind velocity got till 6m/s, the average wind speed of 4m/s is maximum at tested area in July. The maximum power output of 27W in Fig.10, 30W in Fig. 11, and 33W in Fig.12 occur at 4m/s. The variable power output at same wind velocity points out that the wind power intensity is important. The strong and regulated wind is more favourable than intermittent strong wind in power extraction from wind.

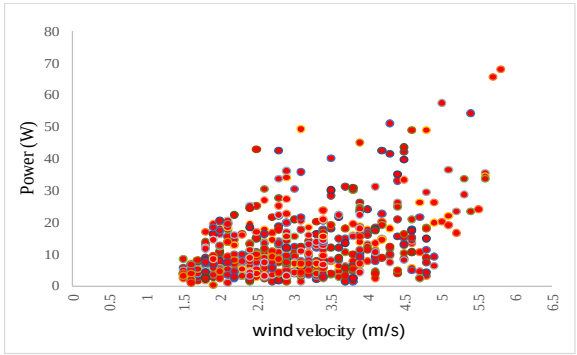


Fig. 13 Scatter plot for power output versus wind velocity from three days' test

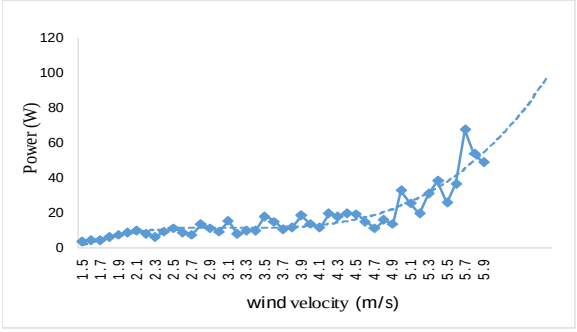


Fig. 14 Scatter plot for average power output versus wind velocity from three days' test

Fig. 13 shows the scatter plot of electrical power output based on variable wind speed range. The data under 1.5 m/s were not mentioned because the wind turbine can't produce electrical power under 1.5m/s. The much more points of scatter power output were occurred at wind velocity between 1.5m/s and 3.75m/s; generate electrical power under 20W. The sparse points of maximum generated power output were occurred between 4.5m/s and 5.9m/s.

The average power outputs from scatter plot shown in Fig. 14. The maximum electrical power output of 49W occurs at wind velocity 5.9m/s. This is the confirmation of wind turbine performance to produce 50W at 6m/s. The trend of power output increases with wind velocity increases.

TABLE II
COEFFICIENT OF PERFORMANCE (CP) VS WIND VELOCITY

Wind velocity (m/s)	Electrical power output (W)	Wind power (W)	Coefficient of performance (Cp)	Power output from wind turbine(W)
4	13.9	73.9664	0.221086	16.35294
4.1	11.8	79.6538	0.174284	13.88238
4.2	20.05	85.6254	0.275482	23.58826
4.3	18.33	91.8883	0.234684	21.56471
4.4	20.32	98.4493	0.242824	23.90585
4.5	19.6	105.315	0.21895	23.05872
4.6	15.47	112.493	0.161787	18.1999
4.7	11.42	119.991	0.111969	13.43527
4.8	16.2	127.814	0.149114	19.05886
4.9	14	135.97	0.121134	16.47059
5	33.13	144.465	0.269797	38.97622
5.1	25.69	153.308	0.197142	30.22345
5.2	19.965	162.504	0.144539	23.48817
5.3	31.07	172.061	0.212442	36.55298
5.4	38.73	181.985	0.250376	45.56468
5.5	26.24	192.284	0.160547	30.87062
5.6	36.93	202.964	0.214063	43.44708
5.7	67.71	214.032	0.372181	79.65864
5.8	54.135	225.496	0.282436	63.68819
5.9	49.2	237.361	0.243857	57.88214

The coefficient of performance of this wind turbine is calculated by using equation (11). The power output from the wind turbine is the product of wind power and coefficient of performance. The average C_P of this wind turbine is 0.23 (23%) for the values of wind velocity from 5m/s to 5.9m/s. With blade optimization, power coefficients of wind turbines reach close to the Betz limit of 59.2%. Small wind turbines operate at 25% or greater efficiency in comparison to large turbines which have performance around 45% [8]. Therefore, this wind turbine design is optimized for the constraints that come with residential use.

CONCLUSION

This three-bladed horizontal-axis wind turbine is intended to use in low-wind speed region. It start-up wind speed is around 3m/s to 3.5 m/s. It cannot turn the wind speed slow down to 0.7 m/s. This wind turbine experimental results should be shown till cut-out wind speed 12 m/s. The much more results should be collected with variable wind speed range from cut-in to cut-out wind speed all the year around because the wind fluctuates all time. The maximum extracted power from this wind turbine will be 350W at 12m/s. All the results prove that the more wind will catch, the more power will get. According to the results, this small horizontal axis wind turbine design has good performance to use in low wind speed regions.

ACKNOWLEDGMENT

The author is deeply gratitude to Dr. Myint Thein, Rector, Mandalay Technological University, for his guidance and advice. The authors wish to express appreciation to all crews at Department of Research and Innovation (DRI) for their help in construction of this project. The author gratefully acknowledges to Dr. Tin San, Associate Professor and Head of Mechanical Engineering Department, Mandalay Technological University. The author would like to express grateful thanks to her supervisor Dr. Myat Myat Soe, Associate Professor, Department of Mechanical Engineering, and to all her teachers from Mandalay Technological University. The author's special thanks are sent to her parents for their guidance from childhood till now.

REFERENCES

[1]. Joshua Earnest, "Wind Power Technology", PHI learning private limited ,2014.
[2]. Siraj Ahmed, " Wind Energy Theory and Practice", Second Edition, 2013.
[3]. Fei-Bin Hsiao, Chi-Jeng Bai and Wen-Tong Chong, "The Performance Test of Three Different Horizontal Axis Wind Turbine (HAWT) Blade Shapes Using Experimental and Numerical Methods", Energies, 2013.
[4]. Ronit K. Singh, M. Rafiuddin Ahmed," Blade Design and Performance Testing of a Small Wind Turbine Totor for Low Wind Speed Applications," SciVerse Science Direct, Renewable energy, pp-812-819,7 Aug 2012.
[5]. John McCosker, "Design and optimization of a small wind turbine", Rensselaer, Polytechnic, Institute, Hartford, Connecticut,2012.
[6]. Duranti Stefano. (2012) homepage on Profili2. [Online]. Available:http://profile-2-professional.software.informer.com/2.3/
[7]. M. Rafiuddin AHMED and Sumesh NARAYAN, "Experimental and numerical studies on a low Reynolds number airfoil for wind turbine blades," Journal of Fluid Science and Technology, Vol.6, No.3, pp. 357-369, 2011
[8]. Fasel H.F, Gross A," Numerical Investigation of Different Wind Turbine Airfoils", Tucson, Orlando, Florida, the University of Arizona,2011.

[9]. Ajao K. R., Adegun I.K," Development and Power Performance Test of a Small Three-bladed Horizontal-axis Wind Turbine" Marsland Press, Journal of American Sciences, pp-70-78, 2009.
[10]. Hermann-Josef Wagner, Jyotirmay Mathur, "Introduction to Wind Energy Systems", Springer Series in Green Energy and Technology ISSN 1865-3529, 2009.
[11]. Hugh Piggott," Small Wind Turbine Design Notes," pp. 4-7, 1998.
[12]. Giguere P, Selig MS," Low Reynolds Number Airfoils for Small Horizontal Axis Wind Turbine," pp. 397,1997.
[13]. Park Jack," The Wind Power Book,"1981.

★★★