Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 03, March-2017

Tail Shape Design of Boat Wind Turbines

Venkatesh Singamsitty, Hong Zhou
Department of Mechanical Engineering
Texas A&M University-Kingsville
Kingsville, Texas, USA

***Abstract*—Wind energy is one of the most reliable renewable energy resources. A lot of research and developments have been going on in wind energy field. Wind turbines are mechanical devices that convert the kinetic energy of wind into electrical power. Boat wind turbines are for small-scale generation of electric power. In order to catch wind power effectively, boat wind turbines need to face wind direction. Tails are used in boat wind turbines to change the wind turbine direction and accommodate the variation of the oncoming direction of wind. They are required to generate a quick and steady response according to the change in wind direction. Tails can have various shapes, and their effects on boat wind turbines are different. However, the effects of tail shapes on the performance of boat wind turbines are not thoroughly studied yet. In this paper, five tail shapes are presented. Their effects on a same boat wind turbine are investigated. The power extraction by the wind turbine is analyzed. The results of this paper provide a guideline of tail shape design for boat wind turbines.**

***Keywords*— Boat Wind Turbine; Tail Shape; Power Extraction; Velocity Stream Line; Simulation.**

I. INTRODUCTION

High energy consumption has now been cited along with an extensive exhaustion of non-renewable energy resources. There is an urgent need to utilize renewable energy resources for energy demands. There exist different renewable energy resources such as solar energy, wind energy, wave energy, tidal energy, geothermal energy [1-2]. Wind energy is one of the most reliable renewable energy resources, and has the merits of no air pollution and zero atmospheric emission. A lot of research and developments have been going on in the wind energy field.

Wind turbines are mechanical devices that convert the kinetic energy of wind into electrical power. A wind turbine is usually termed as a small wind turbine when it produces power of less than 100 kW. Small wind turbines are often used for households, farms, ranches and boats, and are one of the most cost-effective home-based renewable energy systems. Small wind turbines can operate at relatively slow wind speed and have low maintenance cost. They are lightweight and convenient to install. In order to catch wind power effectively, small wind turbines need to face wind direction. Because wind direction changes, the rotor axis of a small wind turbine is usually not aligned to the wind if the wind turbine has a fixed direction and does not provide any yaw motion. In this paper, only horizontal-axis small wind turbines are considered. The yaw motion of a horizontal-axis small wind turbine is the rotation of the rotor axis about a vertical axis. A yawed rotor of a small wind turbine is less efficient than the non-yawed rotor [3]. Tails are used in many small wind turbines to change the wind turbine direction and accommodate the variation of the oncoming direction of wind. Tails are required to generate a quick and steady response according to the change in wind direction and make small wind turbines face the wind.

Boat wind turbines are for small-scale generation of electric power, and usually produce power of less than 350 W. They are often designed like windmills that are small, noiseless and lightweight, and look like pedestal fans that spin on a horizontal axis and oscillate on a vertical axis. The rotor shaft of a boat wind turbine is commonly at the top of a tower. The electrical generator is directly connected to the rotor shaft. The passive yaw motion is adopted in most boat wind turbines in which the wind force is utilized to adjust the orientation of boat wind turbines and make them facing the wind [3]. The number of blades of boat wind turbines is often 3. Three-bladed boat wind turbines can produce power at low wind speed and can be self-started by the wind. This paper is focused on three-bladed boat wind turbines with passive yaw motion.

There are various tail shapes for boat wind turbines. Their effects on boat wind turbines are different. However, the effects of tail shapes on the performance of boat wind turbines are not thoroughly studied yet. The authors of this paper are motived by the challenges facing tail shape design for boat wind turbines. The research objective of this paper is to provide a guideline for designing tail shapes in boat wind turbines.

In this paper, five tail shapes are presented. Their effects on a same boat wind turbine are investigated. The power extraction by the wind turbine is analyzed.

The remainder of the paper is organized as follows. The aerodynamic principles related to boat wind turbines are introduced in section II. The designs and analyses of five tail shapes are provided in section III. Section IV is on the calculations and results of power extraction. Conclusions are drawn in section V.

II. AERODYNAMIC PRINCIPLES OF BOAT WIND TURBINES

The blades in a boat wind turbine generate the lift force that is perpendicular to the direction of the oncoming wind due to the blade shape. The lift force rotates the rotor and the generator within the wind turbine to produce electric power. The blade shape of a wind turbine is described by its airfoil. The chord line that is the straight line connecting the leading and trailing edges on an airfoil divides an airfoil into two surfaces. One surface that is commonly called the upper surface or suction surface is associated with the lower air pressure. The other surface that is called the lower surface or pressure surface has the higher air pressure than the upper surface. The pressure difference between the two surfaces results in the lift force. The blade shape in a boat wind turbine is important for its power generation.

Airfoil design was experience-based in early 20th century. Designers only had past designs and experimental results to guide them. They mainly modified available airfoils for other applications and needs. The situation was totally changed when the airfoil design report [4] from the USA's National Advisory Committee for Aeronautics (NACA) was published. A systematic airfoil design method was established through this landmark report. NACA airfoils are based on two primary design variables, the slope of the airfoil mean camber line and the thickness distribution above and below this line. For sophisticated or special-need airfoil designs, additional design variables can be included [5-6].

The airfoil used for the boar wind turbine in this paper is NACA-4412 as shown in Figure 1, which is from NACA Four-Digit Series. The first digit specifies the maximum camber in percentage of the chord length. The second digit indicates the distance of the maximum camber from the airfoil leading edge in tenths of the chord. The last two digits provide the maximum thickness of the airfoil in percentage of the chord. NACA-4412 airfoil has a maximum camber of 4% of the chord length, which is located 40% (0.4) of the chord length from the leading edge. The maximum thickness is 12% of the chord length. NACA-4412 has flat bottom surface, which prevents the negatively grounded extreme chamber. The overall wing can be seen as rectangular planform. The lift coefficient and drag coefficients are suitable for the small rotor diameters with high speeds and low torques.

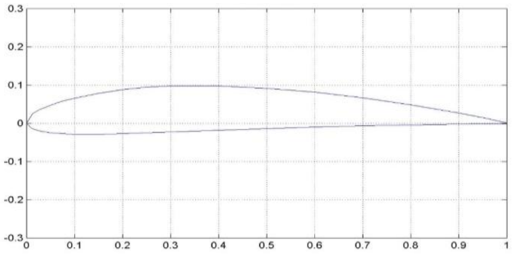

Fig. 1 NACA-4412 airfoil.

A convenient way to establish the ideal tail vane area is to relate it to the swept area of the turbine. The swept area (A) of a wind turbine is the square of the rotor radius (R) times π, which is $A = \pi R^2$. The tail area is usually designed as no lower than 5% of the swept area of the wind turbine. The larger the tail vane area, the more impact the tail has on keeping up the rotor axis toward the wind direction.

Tail can have many different shapes such as square, rectangular, trapezoidal, v-shaped, etc. A tail vane can have a hole or slot within it, or be hole-less. When a tail has a certain area, it can be taller or longer. A tail vane can be centered with the rotor axis, which means half of the tail vane area is above the rotor axis while the other half is below the axis. If a tail vane is not centered with the rotor axis, the entire tail vane can be above or below the rotor axis. The longitudinal position of a tail is usually defined by the distance along the rotor axis between the yaw motion axis (vertical axis) to the area center of the tail vane. The longer the distance, the more impact the tail has on keeping up the rotor axis toward the wind direction. The distance is usually designed as no lower than 110% of the rotor radius. There are many factors from tail vane that have influence on the performance of a boat wind turbine. The authors of this paper endeavor to investigate these factors.

Tip Speed Ratio (TSR) is defined as the ratio between the blade tip speed and the wind speed, and is commonly denoted by λ as shown in Equation (1).

$$\lambda = \frac{blade\ tip\ speed}{wind\ speed} = \frac{\omega R}{v} \tag{1}$$

The blade tip speed is calculated as the product of the angular speed (ω) of the rotor and its radius (R). v is the wind speed. When the λ value is in the range of 1 to 4, the corresponding rotor is usually called a slow rotor. A fast rotor has its λ value from 5 to 7 [7].

Another important factor that affects the performance of a boat wind turbine is its rotor solidity that is defined as the ratio of total rotor planform area to the total swept area and is commonly denoted by σ as shown in Equation (2).

$$\sigma = \frac{total\ planform\ area}{total\ swept\ area} = \frac{Na}{\pi R^2} \tag{2}$$

N in Equation (2) is the number of blades, which is 3 in this paper. a is the planform area from a single blade. If a wind turbine has a low rotor solidity (around 0.1), it is mainly for high speed and low torque case. A low speed and high torque wind turbine usually has a high rotor solidity (around 0.8).

The power coefficient (C_P) of a wind turbine is defined as the ratio of the electric power generated by the wind turbine divided by the total wind power that flows into the swept area of the wind turbine at a specific wind speed. The calculation of C_P is shown in Equation (3).

$$C_P = \frac{electric\ power\ generated}{total\ wind\ power\ into\ turbine} = \frac{P_{out}}{P_{in}} \tag{3}$$

The total wind power (P_{in}) that flows into the swept area of a wind turbine can be calculated based on the wind speed (v), wind density (ρ), and the swept area (A) as follows.

$$P_{in} = \frac{1}{2}\rho v^3 A \tag{4}$$

C_P is a measurement of how efficiently a wind turbine converts the kinetic energy of wind into electric power. It generally changes with the operating conditions such as wind speed and rotor angular speed. Albert Betz was a German physicist who published the well-known Betz's limit in 1919, which states that no wind turbine can convert more than 59.3% (16/27) of the kinetic energy of wind into the mechanical energy that turns a rotor. Betz's limit is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized open disk actuator that extracts the kinetic energy from the wind stream. If a diffuser is employed to augment a bare wind turbine to collect additional wind flow and direct it through the wind turbine, more energy can be extracted from the diffuser augmented wind turbine.

III. DESIGNS AND ANALYSES OF BOAT TAIL SHAPES

As shown in Equation (4), the wind power is proportional to the cube of the wind speed. The inlet air speed is taken as 12.5 m/s in this research.

The tail shapes investigated in this paper are named as T-N-P. The first letter "T" means Tail or Tail Shape. The second letter N is the tail shape number that is from 1 to 5 since five different tail shapes are investigated in this paper. The third letter P represents the position of a tail, which is either A or B. A means the tail shape is aligned above the rotor axis whereas B is for the tail shape aligned below the rotor axis. For example, T-2-B means tail shape number 2 with tail shape aligned below the rotor axis. In this configuration, the tail is at vertically downward position.

Figures 2 to 6 show five different tail shapes that are investigated in this paper. SOLIDWORKS [8] is employed to create the tail models. The blades and the nacelle in the five figures are the same. The sizes and areas of the five tail shapes correspond to each other.

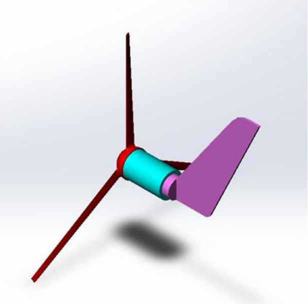

Fig. 2 T-1-A.

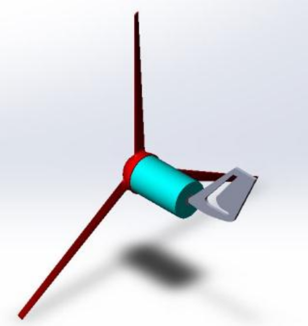

Fig. 3 T-2-A.

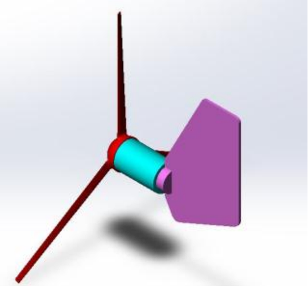

Fig. 4 T-3-A.

The five tail shapes shown in Figures 2 to 6 are all positioned upward. The five downward tail shapes can also be modeled in SOLIDWORKS by rotating the tail part through 180 degrees with respect to the rotor axis. There are totally 10 different tail configurations from the five tail shapes. Each tail shape has two configurations: upward and downward.

The boat wind turbines that have the same blades and 10 different configurations are analysed in ANSYS Workbench [9]. A cylindrical domain is used in this research for creating the turbulence flow of the air. The rotor speed is taken as 1500 rpm with the inlet air velocity of 12.5 m/s. The velocity streamlines of the boat wind turbine with 10 different tail configurations are shown in Figures 7-16.

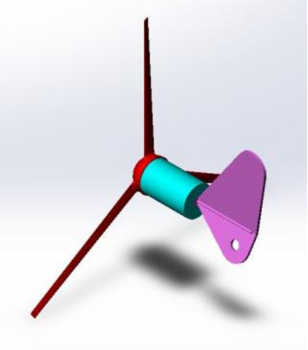

Fig. 5 T-4-A.

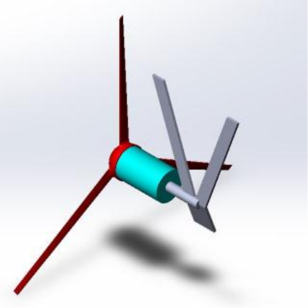

Fig. 6 T-5-A.

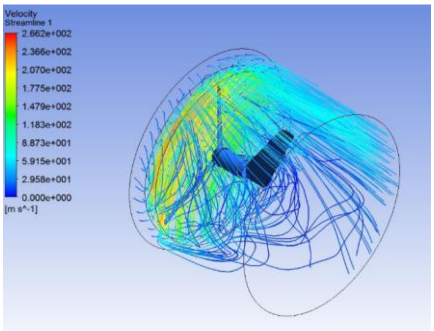

Fig. 7 T-1-A velocity stream lines.

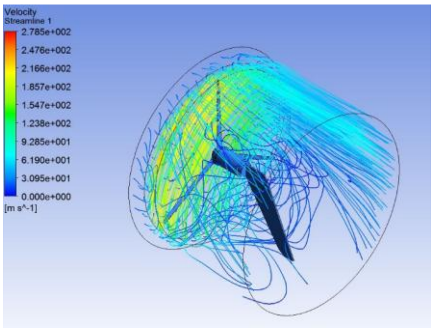

Fig. 8 T-1-B velocity stream lines.

As shown in Figure 7, the air gains more velocity as it goes through the turbine blades. The maximum air velocity reaches to 266.2 m/s for T-1-A. As the air leaves the turbine blades, it loses its velocity. The average air velocity value at the outlet is 12.415 m/s that is from ANSYS. For T-1-B as shown in Figure 8, the maximum air velocity reaches to 278.5 m/s. The average air velocity value at the outlet is 12.381 m/s.

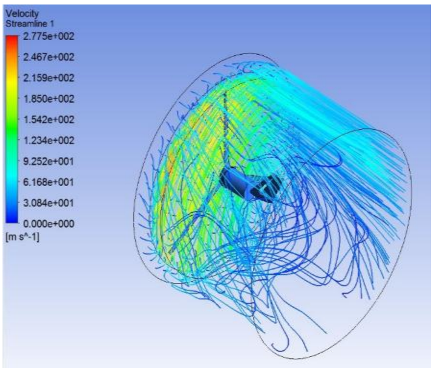

Fig. 9 T-2-A velocity stream lines.

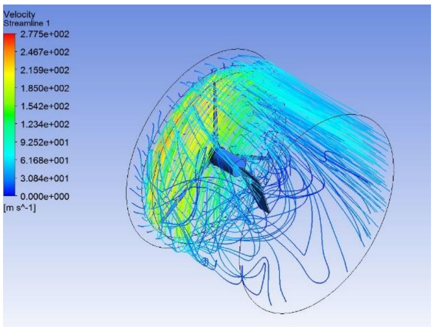

Fig. 10 T-2-B velocity stream lines.

As shown in Figure 9, the maximum air velocity reaches to 277.5 m/s for T-2-A. The average air velocity value at the outlet is 12.388 m/s that is from ANSYS. For T-2-B as shown in Figure 10, the maximum air velocity reaches to 277.5 m/s. The average air velocity value at the outlet is 12.385 m/s.

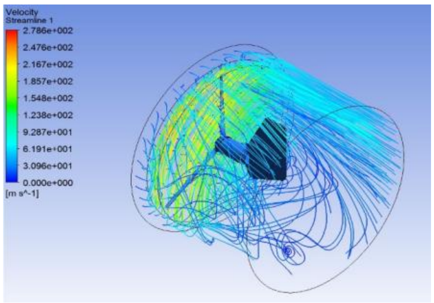

Fig. 11 T-3-A velocity stream lines.

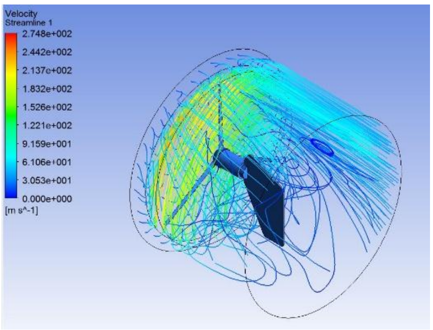

Fig. 12 T-3-B velocity stream lines.

As shown in Figure 11, the maximum air velocity reaches to 278.6 m/s for T-3-A. The average air velocity value at the outlet is 12.410 m/s that is from ANSYS. For T-3-B as shown in Figure 12, the maximum air velocity reaches to 274.8 m/s. The average air velocity value at the outlet is 12.380 m/s.

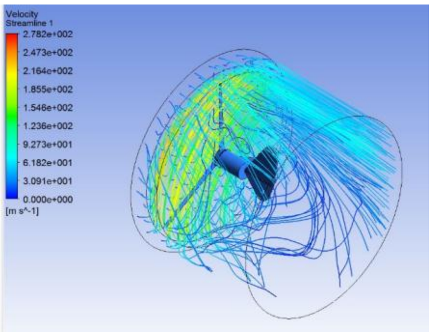

Fig. 13 T-4-A velocity stream lines.

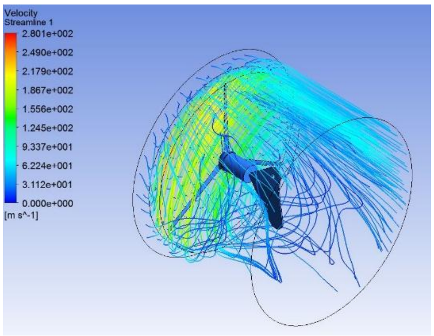

Fig. 14 T-4-B velocity stream lines.

As shown in Figure 13, the maximum air velocity reaches to 278.2 m/s for T-4-A. The average air velocity value at the outlet is 12.425 m/s that is from ANSYS. For T-4-B as shown in Figure 14, the maximum air velocity reaches to 280.1 m/s. The average air velocity value at the outlet is 12.394 m/s.

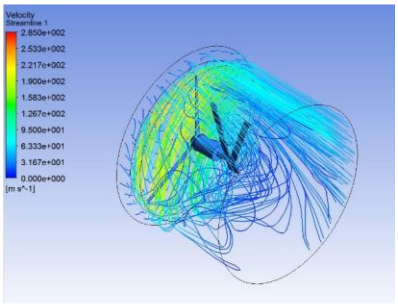

Fig. 15 T-5-A velocity stream lines.

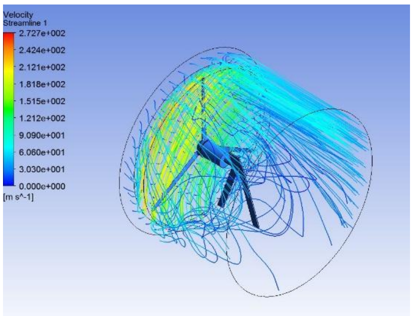

Fig. 16 T-5-B velocity stream lines.

As shown in Figure 15, the maximum air velocity reaches to 285.0 m/s for T-5-A. The average air velocity value at the outlet is 12.391 m/s that is from ANSYS. For T-5-B as shown in Figure 16, the maximum air velocity reaches to 272.7 m/s. The average air velocity value at the outlet is 12.332 m/s.

Among all the streamline velocity profiles, Tail shape T-5-B has the lowest average outlet air velocity of 12.332 m/s, which means that this tail shape has the highest power extraction capability.

IV. CALCULATIONS AND RESULTS OF POWER EXTRACTION

A same cylindrical domain is used to analyse the air flow of the boat wind turbine that has 10 different tail configurations. The inlet air velocity is set as 12.5 m/s. The average outlet air velocity is obtained through the air flow simulation in ANSYS. For the 10 tail configurations, their average outlet air velocity values are as follows.

Tail Shape	Average Outlet Air Velocity (m/s)
T-1-A	12.415.
T-1-B	12.381.
T-2-A	12.388.
T-2-B	12.385.
T-3-A	12.410.
T-3-B	12.380.
T-4-A	12.425.
T-4-B	12.394.
T-5-A	12.391.
T-5-B	12.332.

The air power at both the inlet and outlet of the boat wind turbine can be calculated by Equation (4) that is based on air velocity, air density and the cross sectional area of the cylindrical domain. The inlet air power is the same for all 10 configurations since the air velocity is set at the same value of 12.5 m/s. The air power at the outlet depends on the average outlet air velocity and is different for 10 tail configurations. The air power difference between the inlet and the outlet of the cylindrical domain is the power extraction by the boat wind turbine. The power extracted by the boat wind turbine can be converted into electric power. Therefore, the energy conversion efficiency of the boat wind turbine is proportional to the power extraction. For the 10 tail configurations, their power extraction values are as follows.

Tail Shape	Power Extraction (W)
T-1-A	28.69.
T-1-B	39.97.
T-2-A	37.50.
T-2-B	38.53.
T-3-A	30.36.
T-3-B	40.18.
T-4-A	25.31.
T-4-B	35.01.
T-5-A	36.65.
T-5-B	56.09.

Among the 10 tail configurations, tail shape T-5-B has the highest power extraction whereas tail shape T-4-A has the lowest power extraction. The lowest power extraction is only about 45% of the highest power extraction. The results show that the tail shape of a boat wind turbine has a significant influence on the power extraction of the boat wind turbine.

V. CONCLUSIONS

Tails are used in boat wind turbines for the passive yaw motion in which the wind force is utilized to adjust the orientation of boat wind turbines and make them facing the wind. Five different tail shapes are presented in this paper for a same boat wind turbine that has a horizontal axis and three blades. Each tail shape has two configurations. One is vertically upward and the other is vertically downward. The same boat wind turbine with each of the ten tail configurations is modeled in SOLIDWORKS and simulated in ANSYS Workbench for power extraction. A same cylindrical domain is employed for the simulation and analysis of the air flow in the boat wind turbine. The inlet air velocity is set at 12.5 m/s. The average outlet air velocity is obtained from ANSYS simulation. The power extraction of the boat wind turbine with each tail configuration is calculated based on the inlet and outlet air velocities. The simulation and calculation results show that tail shape T-5-B has the highest power extraction. The lowest power extraction is from tail shape T-4-A, which is only about 45% of the highest power extraction.

REFERENCES

[1] R.D. Begamudre, Energy Conversion Systems. New Age International Publisher, New Delhi, 2000.

[2] B.H. Khan, Non-Conventional Energy Resources. Tata McGraw-Hill, New Delhi, 2006.

[3] C.R. Nikhil, A.K. Sandip, “Effect of Tail Shapes on Yawing Performance of Micro Wind Turbine,” International Journal of Energy and Power Engineering, 2015, 4(5-1): 38-42.

[4] E.N. Jacobs, K.E. Ward, R.M. Pinkerton, The Characteristics of 78 Related Airfoil Sections from Tests in the Variable Density Wind Tunnel. National Advisory Committee for Aeronautics, Hampton, Virginia, 1933.

[5] C.L. Ladson, C.W. Brooks, Development of a Computer Program to Obtain Ordinates for NACA 4-Digit, 4-Digit Modified, 5-Digit, and 16 Series Airfoils. National Advisory Committee for Aeronautics, Hampton, Virginia, 1975.

[6] C.L. Ladson, C.W. Brooks, A.S. Hill, D.W. Sproles, Computer Program To Obtain Ordinates for NACA Airfoils. National Advisory Committee for Aeronautics, Hampton, Virginia, 1996.

[7] A. Sarkar, D.K. Behera, “Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy,” International Journal of Scientific and Research Publications, 2012, 2(2): 1-5.

[8] R.H. Shih, P.J. Schilling, Parametric Modeling with SOLIDWORKS 2016. 5442 Martway Drive, Mission, KS: SDC Publications, 2015.

[9] H.H. Lee, Finite Element Simulations with ANSYS Workbench 16. 5442 Martway Drive, Mission, KS: SDC Publications, 2015.