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Blade Analysis of HAWT Using BEM Approach

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Abstract

Wind energy is an abundant natural resource that people have been trying to tap in recent decades. More and more wind turbines are being built to solve the world's energy shortage problem. To make optimum aerodynamic design of wind turbine blades, blade element momentum theory (BEMT) is widely used due to its effectiveness in design and rapid calculation. The computational method is very useful for understanding the aerodynamic characteristics of rotor blades, but it consumes too much time and resources; thus it is generally applied at the final performance evaluation stage after all the design process is completed. In this study, aerodynamic design for variable -speed variable pitch type 3 -MW wind turbine blade was completed and analysis results by BEMT and CFD were compared.

Keywords: *wind turbine, aerodynamic, wind speed, rotor*

1. Introduction

A wind turbine uses rotor blades to extract and convert kinetic energy of wind into electrical energy. Therefore, a rotor blade requires optimal aerodynamic shape to maximize its efficiency and to improve power performance. There have been various researches using computational fluid dynamics (CFD) to identify the blade performance and flow characteristics. As CFD analysis utilizes the three-dimensional Navier-Stokes equation as the governing equation, it has the advantage of providing more accurate result of analysis compared to previous aero-elastic code. On the contrary, to acquire reliable result from computational method, a vast amount of computational grids are required and advanced turbulence model needs to be applied. The computational method is very useful for understanding the aerodynamic characteristics of rotor blades, but it consumes too much time and resources; thus it is generally applied at the final performance evaluation stage after all the design process is completed. In this study, aerodynamic design for variable -speed variable pitch type 3 -MW wind turbine blade was completed and analysis results by BEMT and CFD were compared. In addition, flow characteristics on the blade surface are presented for reference.

2. Working of HAWT

In this section the basics of the functioning of modern HAWT are briefly summarized. Since the transformation of wind energy into electricity is not obtained directly, but consists of many complicated steps (and passing through the mechanical energy form). The latest technologies of aerodynamics, mechanics, control systems and electro technology are involved in such process. The fig. 1 shows power generation process of a wind turbine. Wind turbine blades are affected by a force distribution, which results in a mechanical torque at the rotor shaft and the rotor itself rotates. In modern airscrew that aerodynamic driving force is mainly a lift force, like for the air-craft flight, rather than drag force like it is in ancient sailing ships. The shaft transfers the torque from the blades to the generator, but this passage can be achieved indifferent ways.

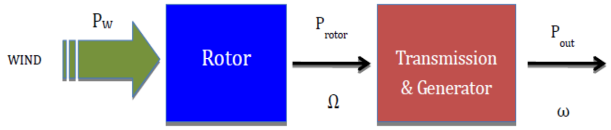

Fig. 1 Power generating process of a wind turbine [14]

The start-up wind velocity (cut - in) of a wind turbine is about 3-5 m/s. While the wind speed increases the power production growths too, till the rated power is reached and then the exceeding output is limited. At a fixed value of wind speed (cut-off), typically around 25 m/s the turbine stops for safety reasons (standstill). For the correct functioning of a wind turbine control systems are therefore needed. Until rated power is reached, those systems should make the turbine work with the maximum efficiency, whereas after the peak the target is keeping the power constant.

3. Blade Element Momentum (BEM) theory

Loads and performance calculations of wind turbines are today routinely performed by the Blade -Element Momentum method. The method is indeed computationally cheap and thus very fast, even with providing very satisfactory results. [16]

The BEM method consists on dividing the flow in annular control volumes and applying momentum balance and energy conservation in each control volume. The annuli are bounded by stream surfaces that enclose the rotor and extend from far upstream to far downstream as shown in fig. 2.

Basic assumptions of the method are that the induced velocity in the rotor plane is equal to one half of the induced velocity in the ultimate wake, and that the flow can be analyzed by dividing the blade into a number of independent elements. Moreover the loads for each blade are uniformly distributed azimuth -wise, which means the rotor would have an infinite number of blades.[6]

For each blade element, the aerodynamic forces are obtained using tabulated airfoil data, which stem from wind tunnel measurements and corrected for three-dimensional effects. The BEM could be a design as well as a verification method. When using BEM as a design method, the following inputs and outputs are defined:

- INPUT:

Rated power P, power coefficient C_p, mean wind speed V_0, number of blades B

- OUTPUT:

Rotor diameter D, chord c_i (r) and twist θ_i (r) radial distribution

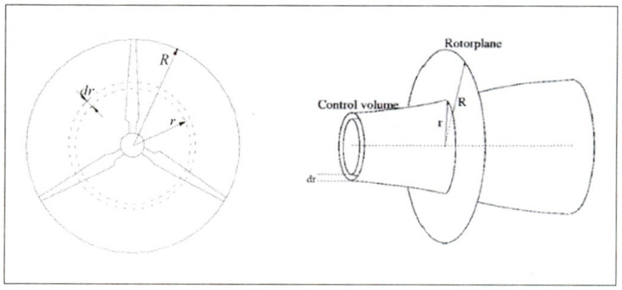

Fig. 2 BEM annular control volumes

the momentum theory is tried to be explained on account of HAWT rotor design but it does not consider the effects of rotor geometry characteristics like chord and twist distributions of the blade airfoil. For this reason blade element theory needs to be added to the design method. In order to apply blade element analysis, it is assumed that the blade is divided into N sections. This analysis is based on some assumptions including no aerodynamic interactions between different blade elements and the forces on the blade elements are solely determined by the lift and drag coefficients. Since each of the blade elements has a different rotational speed and geometric characteristics they will experience a slightly different flow. So blade element theory involves dividing up the blade into a sufficient number (usually between ten and twenty) of elements and calculating the flow at each one as shown in fig. 3, 4). Overall performance characteristics of the blade are then determined by numerical integration along the blade span. [11]

Lift and drag coefficient data are available for a variety of airfoils from wind tunnel data. Since most wind tunnel testing is done with the airfoil stationary, the relative velocity over the airfoil is used in order to relate the flow over the moving airfoil with the stationary test as shown in fig. 5.

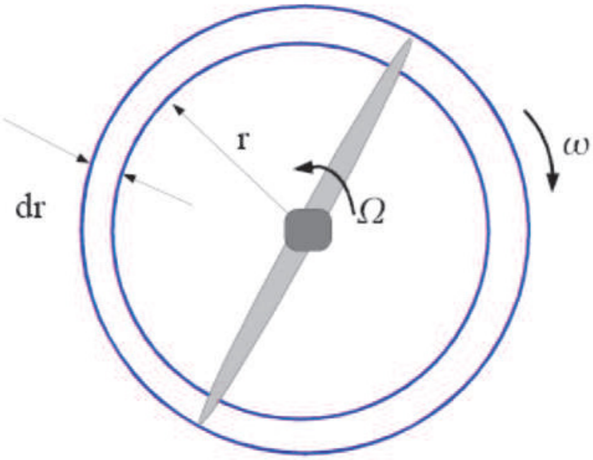

Fig. 3 Rotating Annular Stream Tube

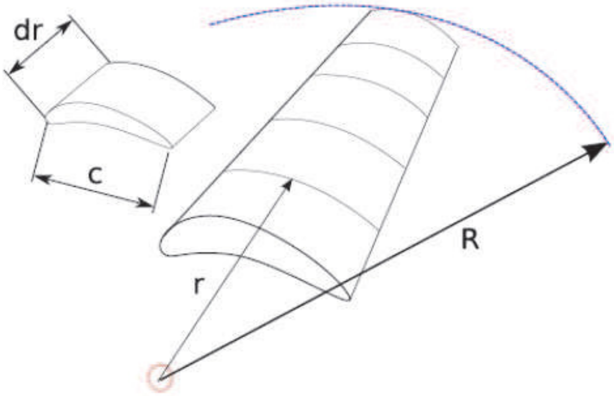

Fig. 4 The Blade Element Model [11]

Examining Fig. 5, the following equations can be derived immediately

$$U_{rel} = \frac{U_\infty(1-a)}{\sin\varphi} \tag{1}$$

$$\tan\varphi = \frac{U_\infty(1-a)}{\Omega r\,(1+a')} = \frac{(1-a)}{(1+a')\lambda_r} \tag{2}$$

$$dL = dF_L \sin\varphi - dF_D \cos\varphi \tag{3}$$

$$dT = dF_L \cos\varphi + dF_D \sin\varphi \tag{4}$$

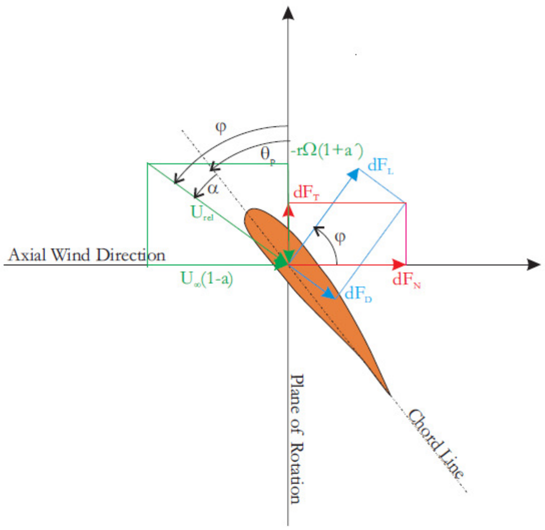

Fig. 5 Blade Geometry for the analysis of a HAWT Rotor [11]

The equations can be rearranged as,

$$dL = B\frac{1}{2}\rho U_{rel}^2 (C_L \sin\varphi - C_D \cos\varphi)cdr \tag{5}$$

$$dT = B\frac{1}{2}\rho U_{rel}^2 (C_L \cos\varphi + C_D \sin\varphi)cdr \tag{6}$$

In order to calculate the induction factors *a* and *a'*, Cd can be set to zero. Thus the induction factors can be determined independently from airfoil characteristics.

$$a = \frac{1}{\left[\left[\frac{4\cos\varphi}{(\sigma C_L)}\right] - 1\right]} \tag{7}$$

$$\frac{a}{a'} = \frac{\lambda_r}{\tan\varphi} \tag{8}$$

$$C_L = \frac{4\sin\varphi\,(\cos\varphi - \lambda_r \sin\varphi)}{\sigma\,(\sin\varphi + \lambda_r \cos\varphi)} \tag{9}$$

The total power of the rotor can be calculated by integrating the power of each differential annular element from the radius of the hub to the radius of the rotor [14].

$$P = \int_r^R dP = \int_r^R \Omega dQ \tag{10}$$

$$C_P = \frac{P}{1/2\rho U_\infty^3 A} = \frac{\int_r^R \Omega dQ}{\frac{1}{2}\rho U_\infty^3 \pi r R^2} \tag{11}$$

4. BEM – Designed blade geometry

A wind turbine uses rotor blades to extract and convert kinetic energy of wind in to electrical energy. Therefore, a rotor blade requires optimal aerodynamic shape to maximize its efficiency and to improve power performance. To make optimum aerodynamic design of wind turbine blades, blade element momentum (BEMT) theory is widely used due to effectiveness in design and rapid calculation. Aerodynamically, the evaluated values such as electrical power, power coefficient, axial thrust force, annual energy production (AEP) are concerned to secure design effectiveness of rotor blades. A typical design process starts with determining blade length and rated rotating speed according to design class and specification, and then design parameters such as blade chord length, twist angle and airfoil distribution is obtained by using BEMT to construct a blade plan form for baseline blade.

4.1 Initial design conditions

Wind turbine blade design starts from deciding the IEC Class as in Table 1, 2.Wind turbine class is defined as the values of reference wind speed (V_{ref}) and turbulence intensity (I15). Reference wind speed is the 10 minutes -averaged value for extreme wind speed which has the recurrence period of 50 years at the height of hub, and turbulence intensity is the value of turbulence intensity with the condition of 10minutes averaged wind speed of 15 m/s at the height of hub.

By considering the blade design for offshore wind power generation IEC Class IB has selected (high reference wind speed and low turbulence intensity).

Table 1: Basic parameters for wind turbine classes, IEC 2nd Ed.[17]

Class		I	II	III	IV	S
V_{ref} *(m/s)*		50	42.5	37.5	30	Values specified by
V_{ref} *(m/s)*		10	8.5	7.5	6	
	I_{15}	0.18	0.18	0.18	0.18	

A	*a*	2	2	2	2	designer
B	I_{15}	0.16	0.16	0.16	0.16	
	a	3	3	3	3	

Table 2 shows the initial design factors for 3 MW blades calculated from nominal generator speed of 1800 rpm and gear ratio of 131:1. λ_{design} is defined as design tip speed ratio which is normally set at the range of 7 ~ 9 in large wind turbines; as the value of λ_{design} gets bigger, the blade will be more slender and flexible. A slender blade has the advantage of reducing the load; however, it may cause an interference problem between tower and blade at extreme wind condition and the blade rotation speed may need to be increased to acquire the targeted power output. On the contrary, with a smaller value of λ_{design}, the blade will be thickened and it causes greater axial thrust force. Therefore, it is very important to set the proper value of λ_{design} [4]

Table 2: Basic design parameter [17]

Rated power	3MW	Swept area	7058 m^2
Rated wind speed	12.1 m/s	Rotor speed	15.11 rpm
Diameter	94.8 m	Material	GERP
Number of blades	3	Power loss	0.855
Design class	IB	λ_{design}	7.5
Generator Speed	1800 rpm	Gear ratio	131:1

Table 3: Final development goal of 3MW blade [17]

Items	*Specifications*
Diameter / mass	94.8 m (11 – 12 ton)
External environmental condition	IEC class IB, 2nd edition
Power output	3MW (V_{rated} = 12 m/s)
Efficiency	About 0.5 (aerodynamic)

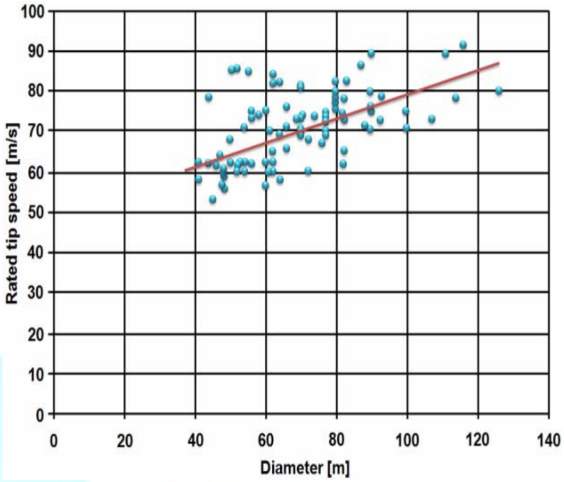

Fig.6 Tendency of rated tip speed variation

Fig. 6 shows blade tip speed changing trend per capacity change of the modern wind turbine. For this research, tip speed is restricted to 75 m/s by referencing the trend in Fig. 6. An offshore wind turbine is less restricted compared to onshore wind turbine in blade tip speed. However, the interference problem between blade and tower could occur if blade tip speed is too high.

5. Performance analysis by BEM code

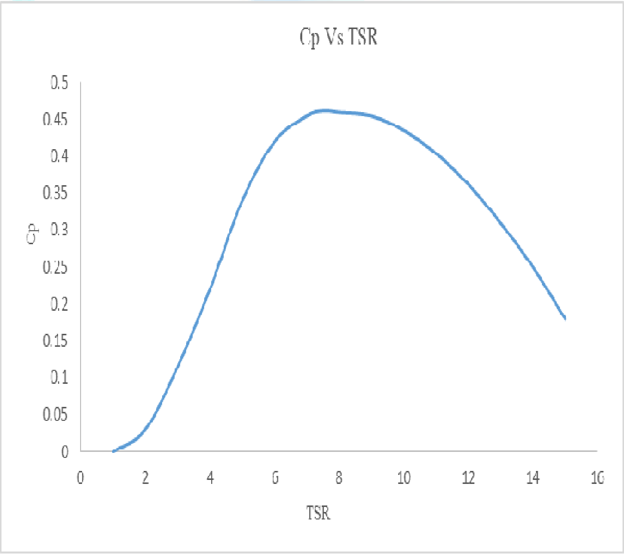

Fig. 7 Cp – TSR curve

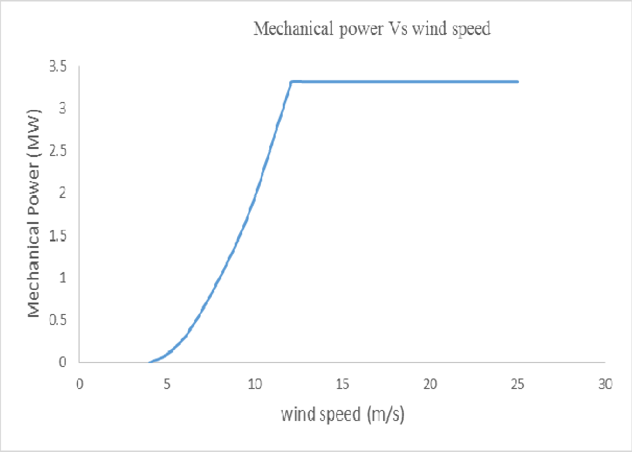

Fig. 8 Mechanical power – wind speed curve.

GH-Bladed is integrated load calculation software developed by Garrard-Hassan and widely used to calculate aerodynamic and structural loads of wind turbine system. Its aerodynamic calculation module is based on BEM theory; thus it is chosen to predict blade power performance in this study. Fig. 7 shows the changes in mechanical power for variation of λ. λ_{design} value was 7.5 as mentioned in design stage, and maximum efficiency occurred at the design λ with CP max of 0.462.

Fig. 8 shows the mechanical power distribution of design blade for variable wind speeds. Mechanical power turns into electrical power as it goes through drive train and generator. Since the goal of this research was to design a blade which generates 3 MW of electrical power, the mechanical power shown in Fig. 8 is always higher than electrical power due to the system loss. At rated condition, mechanical power is predicted a value of 3.31 MW along with 394.5 kN of thrust force and it meets the criteria with condition of rated wind speed at 12.1 m/s. The wind power generation system controls generator torque at below rated wind speed to continuously maintain maximum efficiency. It also controls blade pitch to regulate power output at the rated level in the region above rated wind speed. To find proper blade pitch angles above rated wind speed, numerical iteration is required for pitch angles at each wind speed.

Pitch schedule map shown in Fig. 9 is made by acquiring pitch angle of the points where electrical output becomes 3.0 MW.

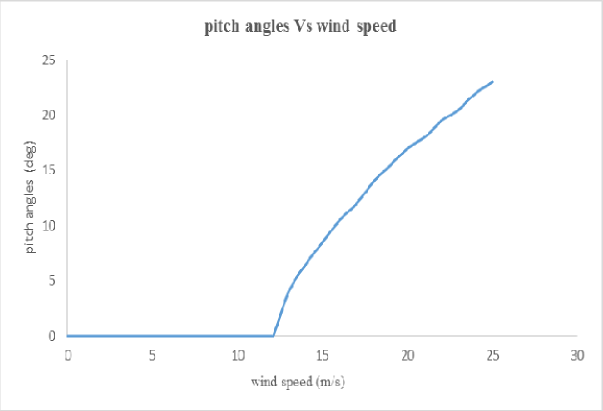

Fig. 9 Pitch schedule curve.

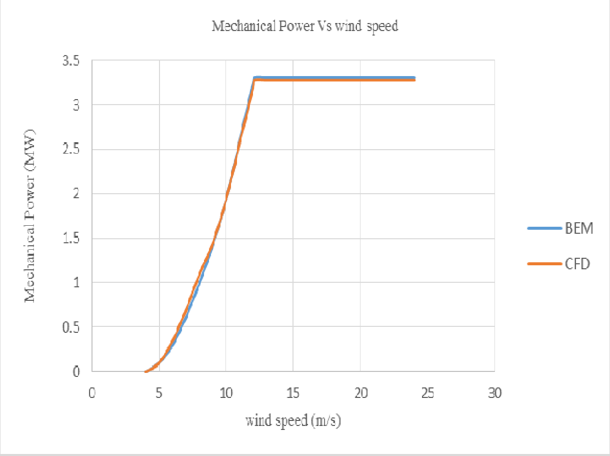

Fig. 10 Comparison of mechanical power.

Comparison of results from BEM and CFD code is studied as shown in fig. 10. The comparison is done for the wind speed range of 5 to 12.1 m/s. After achieving the target of rated power, the power generation is controlled by changing pitch angle.

The mechanical power generated by turbine rotor at 12.1 m/s is 3.31 MW whereas by CFD, the value came 3.28 MW. The result of CFD analysis at wind speeds 6, 7 and 8 m/s shows higher value compared to that of BEM. It shows that that the CFD result is relatively in good agreement with the result of BEM both qualitatively and quantitatively throughout the wind speed range.

6. Conclusions

Aerodynamic design of 3 MW wind turbine blade is carried out using BEMT, and performance analysis is performed by BEMT and CFD code. The targeted maximum power output is generated at design wind speed of 10m/s and 3.3 MW is produced at rated wind speed of 12.1m/s. The Blade element momentum theory is used and applied for aerodynamic design of the wind Turbine and is reported the acceptance of its results. By comparing the maximum power coefficient, CFD predicted about 3.5% higher value than GH-Bladed and thrust force is qualitatively well agreed in all of the wind conditions.

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