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Horizontal Axis Wind Turbine Performance Analysis

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Abstract.: The present work uses the method of Blade Element Momentum Theory as suggested by Hansen. The method applied to three blade models adopted from Rahgozar S. with the airfoil data used the data provided by Wood D. The wind turbine performance described in term of the thrust coefficient C_T, torque coefficient C_Q and the power coefficient C_p . These three coefficient can be deduced from the Momentum theory or from the Blade element Theory(BET). The present work found the performance coefficient derived from the Momentum theory tent to over estimate. It is suggested to used the BET formulation in presenting these three coefficients. In overall the Blade Element Momentum Theory follows the step by step as described by Hansen work well for these three blade models. However a little adjustment on the blade data is needed. To the case of two bladed horizontal axis wind turbine, Hansen's approach works well over if the blade radius is R_B the calculation should start from r = $0.1R_B$.

Key Words: Blade element theory, momentum theory, wind turbine, power coefficient

1. Introduction

It is true that there are various wind turbine configuration had been in operation. Although there various type of wind turbine, basically the type of wind turbine can be classified in to two basic types of wind turbines, they are namely (1) The Vertical Axis Wind Turbine and (2) The Horizontal Axis Wind Turbine (HAWT) [1]. These two types of wind turbine are distinguished by the manner its axis of wind turbine oriented with respect to the incoming wind direction. The vertical axis wind turbine is the wind turbine where the axis rotation of wind turbine is in perpendicular with respect to the incoming wind direction. While the horizontal axis wind turbine is used to describe a class wind turbine which the wind turbine's axis rotation is a parallel to the incoming wing. The Savonius wind turbine, Darrius wind turbine and a straight bladed vertical axis wind turbine are examples of type wind turbine belong to the class of vertical axis wind turbine [2]. While a single bladed, or double bladed or three blade horizontal axis wind turbine together with U.S farm wind mill and Enfield-Andreau wind turbine are examples of wind turbine belong to the class of the horizontal axis wind turbine [3]. It is true that there are some advantages gaining by the vertical axis wind turbine compared to its counterpart. The Vertical axis wind turbine does not have to adjust to the wind direction so the nacelle and a yaw system are not required. In addition to this Also all heavy components, for example a generator, may be installed close to the ground. Thus, the overall cost is lower in comparison with the horizontal axis wind turbine. However, the vertical axis wind turbine in view of the ability to extract wind kinetic energy is less efficient compared to the horizontal axis wind turbine. This may the reason way the most wind turbines are dedicated for electricity power generator use a horizontal axis wind turbine[4]. It is necessary to be noted since 2019, the total capacity of wind turbine to generate electricity is around 623 Giga watt (Gw) producing 1423 (Terra watt hours) Twh. Table 1.1 shows some countries which they are already utilize

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wind energy as the energy resources for electricity generation, which shows currently China represent the biggest country already utilized wind energy.

Table 1 - Wind turbine installed capacity in Gw[5]

Country	**Installed capacity in Giga watt (Gw)**			**New capacity (Gw)**
	2018	2019	2020	2020
China	209.53	237.03	290.0	52.0
US	96	105.4	122.33	16.8
Germany	59.3	61.26	62.63	1.43
India	35.13	57.53	38,63	1.1
Spain	23.5	25.8	27.45	1.64
UK	20.74	23.52	24.18	0.6
France	15.31	15.45	18.01	1.30
Brazil	14.70	15.45	18.01	2.56
Canada	12.82	13.41	13.59	0.175
Italy	9.96	10.51	10.85	0.280
Rest of the world	92.2	104.0	119.3	94.0

It is necessary to be noted that the Horizontal axis wind turbines (HAWT) are the predominant turbine design in use today in USA. It is seemed that other countries have the same trend. The HAWT come in a variety of sizes, ranging from 2.5 meters in diameter and 1 kW for residential applications to 100+ meters in diameter and 10+ MW for offshore applications. It clear the HAWT play an important role in harnessing wind energy [6]. Considering the wind speed is always changing from time to time, it is there the capability in predicting the HAWT performance is important. Through such capability, one will be able to predict how the power can be produced over an interval time with the wind speed is always change. To do this the present work uses the Blade Element Momentum Theory according to Hansen[13]. The blade geometry use the blade model as it had be used by Rahgozar et all.[14]. The wind turbine performance analysis presented in term of power coefficient Cp plotted again the tip speed ratio λ for different number of blade and different airfoil section. The result shows that the as suggested by Hansen[13] fully work for particular blade geometry and airfoil data. However a little adjustment to the data is required.

2. The Combined Blade Element and Momentum Theory

Wind turbine is a device designed to extract the wind kinetic energy to become a useful mechanical power. Here one can consider that the wind turbine can be regarded as a system with wind velocity U_∞, air density ρ, air viscosity μ and the radius turbine blade R_B as input variables, and shaft torque Q, shaft frequency n and the axial force in the wind direction (Thrust) T and power P output as the output variables. The Power output P is torque multiply by the turbine angular velocity Ω as $P = \Omega Q$ and $\Omega = 2\pi n$. These output variables describe the capability of the device in converting wind kinetic energy to become a useful power and they are normally presented in non- dimensional parameter as :

$$\text{Power coefficient } C_p = \frac{P}{\frac{1}{2}\rho U_\infty^3 A} \tag{1}$$

$$\text{Torque coefficient } C_Q = \frac{Q}{\frac{1}{2}\rho U_\infty^2 A R_B} \tag{2}$$

$$\text{Thurst coefficient } C_T = \frac{T}{\frac{1}{2}\rho U_\infty^2 A} \tag{3}$$

$$\text{Tip speed ratio } \lambda = \frac{\Omega R_B}{U_\infty} \tag{4}$$

The variable A in above equation is the wind turbine swept area which here is equal to πR_B^2. The performance of the wind turbines are normally presented in term of these three coefficients and calculated at different value of tip speed ratio λ. Variation of tip speed ratio can be considered as the variation of wind speed. There are various method had been developed for evaluating the wind turbine performance.

The most advance technique for evaluating the wind turbine performance may solution based a computational fluid dynamics. One example of this method is the 3-D hybrid Navier-Stokes/potential flow solver developed at Georgia Tech for helicopter rotor and propeller applications to horizontal axis wind turbines[6]. This method use a three-dimensional unsteady compressible Navier-Stokes equations are solved in a small region, on a body-fitted grid surrounding the rotor blade and the potential flow equation is solved. away from the blades, the vorticity shed at the blade tip is captured using a Lagrangean representation of the tip vortices. While the second example of the use CFD for solving the performance of wind turbine is the method based a Reynolds-averaged Navier-Stokes equation. This system equation is solved by using an implicit finite difference approach with overset grids. The method is first-order accurate in time with fourth-order central differences for spatial differences added with a second- and fourth-order central difference dissipation terms for stability [8]. This method in the form computer code is named OVERFLOW and written by Buning et, al.,[9]. Since then, various versions of OVERFLOW have been developed and applied to both rotorcraft[10] and to HAWTs[11]. The other method may one use a method belong to the class of lifting line combined with a prescribed wake model [12] or a free wake model [13]. These mentioned methods beside provide the power coefficient, these methods are able to provide additional information such as the flow pattern surrounding the blade. However, for the purpose of wind turbine design, the Blade Element Momentum theory may represent the most common method in this design work[14,15].

The Blade Element Momentum method couples the momentum theory with the local events taking place at the actual blades (The Blade Element Theory). The stream tube introduced in the 1-D momentum theory is discretized into N annular elements of height dr, as shown in Fig. 1. The lateral boundary of these elements consists of streamlines; in other words there is no flow across the elements. Here one can assume that the flow at each the annular elements, (1) No radial dependency and (2) The force from the blades on the flow is constant in each annular element.

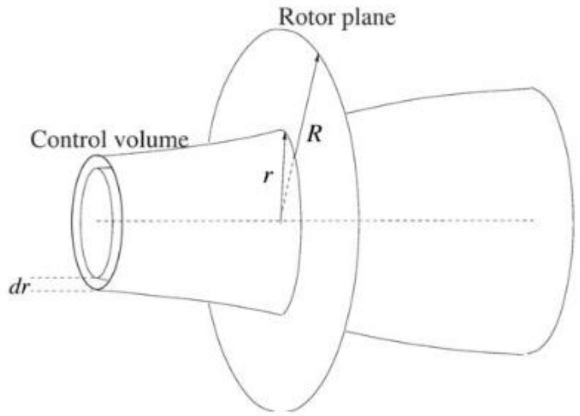

Fig. 1 - The annular element shape for the Momentum Theory

While the Blade Element Theory assumes that blades can be divided into small elements that act independently of surrounding elements and operate aerodynamically as two-dimensional airfoils whose aerodynamic forces can be calculated based on the local flow conditions. These elemental forces are summed along the span of the blade to calculate the total forces and moments exerted on the turbine. As result at each blade segment will experience the velocity and forces are drawn diagrammatically as shown in the Fig. 2.

Fig. 2 shows that the blade section at a distance r from the blade axis rotation. The incoming velocity and the rotational motion of the blade makes the axial velocity $U_x = U_\infty(1-a)$ and the tangential velocity $U_t = \Omega r(1+a')$.

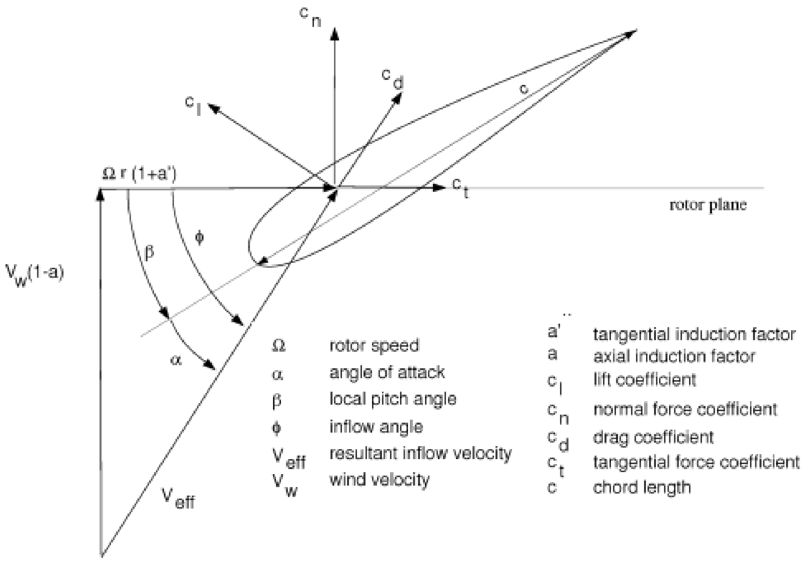

Fig. 2 - Velocities and forces work at the blade section[16]

At the time the wind cross the blade the axial velocity U_x reduce from U_∞ by a factor aU_∞ , where a is the axial induction factor. While in tangential direction U_t increases by $a'\Omega r$ with a' is the angular induction factor. If these two quantities a and a' are known, the effective velocity U_{eff} and the inflow angle Φ at that section can be defined. As result for a given the pitch blade angle β, the angle of attack α can be defined. Hence for known a and a', the inflow angle Φ and the angle of attack α can be defined, namely :

$$tg\ \Phi = \frac{U_x}{U_t} = \frac{U_\infty(1-a)}{\Omega r(1+a')} \tag{5}$$

And,

$$\alpha = \Phi - \beta \tag{6}$$

Using a look up airfoil data for a given angle of attack α, one can obtain the lift coefficient C_L and the drag coefficient C_D. Hence the differential thrust dT and the differential tangential force dF_t also the differential torque dQ for N_B bladed wind turbine configuration in which at the blade element Δr, the value C_L and C_D are known become:

$$dT_{BET} = \frac{1}{2}\rho U_{eff}^2\, c_r\, C_x\, N_B\, \Delta r \tag{7}$$

$$dF_{t\,BET} = \frac{1}{2}\rho U_{eff}^2\, c_r\, C_t\, N_B\, \Delta r \tag{8}$$

$$dQ_{BET} = r\, dF_{t\,BET} \tag{9}$$

Where :

$$U_{eff}^2 = U_x^2 + U_t^2 = \left(U_\infty(1-a)\right)^2 + \left(\Omega r(1+a')\right)^2 \tag{10a}$$

$$C_x = C_L \cos\Phi + C_D \sin\Phi \tag{10b}$$

$$C_t = C_L \sin\Phi - C_D \cos\Phi \tag{10c}$$

c_r : local chord length

The differential thrust dT_{BET}, Eq. (7) and differential torque dQ_{BET}, Eq. (9), in term of axial and angular induction factors (a and a') can be written as:

$$dT_{BET} = \sigma\,\rho \frac{\left(U_\infty(1-a)\right)^2}{\sin^2\Phi}\left[C_L\ cos\ \Phi + C_D sin\ \Phi\ \right]\pi r\,\Delta r \tag{11}$$

And

$$dQ_{BET} = \sigma\rho \frac{\left(U_\infty(1-a)\right)^2}{\sin^2\Phi}\left[C_L\ sin\ \Phi - C_D cos\ \Phi\ \right]\pi r^2\,\Delta r \tag{12}$$

Where

$$\sigma = {(N_B c_r)}\big/{(2\pi r)} \tag{13}$$

The quantity σ in above equation is called as a solidity factor. The differential thrust and torque formulated by the While Momentum theory, can be written as [16]:

$$dT_{MOM} = \rho U_\infty^2\, 4a\,(1-a)\,\pi r\,\Delta r \tag{14}$$

And

$$dQ_{MOM} = \rho U_\infty\, 4a'\,(1-a)\,\pi r^3\,\Omega\Delta r \tag{15}$$

Quoting Eq. (11) with Eq. (14) and the Eq.(12) with Eq.(15) one will obtain two equations with two unknown a and a' , namely :

$$dT_{BET} = dT_{MOM}$$

$$\sigma\,\rho \frac{\left(U_\infty(1-a)\right)^2}{\sin^2\Phi}\left[C_L\ cos\ \Phi + C_D sin\ \Phi\ \right]\pi r\,\Delta r = \rho U_\infty^2\, 4a\,(1-a)\,\pi r\,\Delta r$$

$$\sigma\,\frac{(1-a)}{\sin^2\Phi}\left[C_L\ cos\ \Phi + C_D sin\ \Phi\ \right] = 4a$$

$$\frac{a}{1-a} = \frac{\sigma}{\sin^2\Phi}\left[C_L\ cos\ \Phi + C_D sin\ \Phi\ \right] \tag{16}$$

Or

$$a = \frac{1}{\frac{4\sin^2\Phi}{\sigma\left[C_L\ cos\ \Phi + C_D sin\ \Phi\ \right]} + 1} \tag{17}$$

While from quoting dQ_{BET} , Eq. (12) and dQ_{MOM} , Eq. (15), one can obtains:

$$dQ_{BET} = dQ_{MOM}$$
$$\sigma\, \rho \frac{\left(U_\infty(1-a)\right)^2}{\sin^2 \Phi}[C_L \; sin\, \Phi - C_D cos\, \Phi\,]\pi r^2\, \Delta r = \rho U_\infty\, 4a'\,(1-a)\,\pi r^3\, \Omega \Delta r$$
$$\sigma\, \frac{U_\infty(1-a)}{r\Omega}\frac{1}{\sin^2 \Phi}[C_L \; sin\, \Phi - C_D cos\, \Phi\,] = 4a'$$
$$\sigma\, (1+a')\tan \Phi \frac{1}{\sin^2 \Phi}[C_L \; sin\, \Phi - C_D cos\, \Phi\,] = 4a'$$

$$\sigma\, (1+a') \frac{1}{\sin \Phi \cos \Phi}[C_L \; sin\, \Phi - C_D cos\, \Phi\,] = 4a' \tag{18}$$

Or

$$a' = \frac{1}{\frac{4\, sin\, \Phi cos\, \Phi}{\sigma(C_L\; sin\, \Phi - C_D cos\, \Phi)} - 1} \tag{19}$$

In defining the axial and angular induction factor as given by Eq. (17) and Eq.(19), with no influence of vortices shed from the blade tips into the wake on the induced velocity field. Prandtl introduce the correction factor to include the effects of vortices by a correction factor to the induced velocity field, F, in the form :

$$F = \frac{2}{\pi}\cos^{-1}\left(e^{\,-\frac{N_B}{2}\left(\frac{R_B - r}{r \sin \Phi}\right)}\right) \tag{20}$$

In the presence of tip loss factor f, make the axial and angular induction factors a and a' becomes:

$$a = \frac{1}{\frac{4\,\mathrm{F}\sin^2 \Phi}{\sigma[C_L\; cos\, \Phi + C_D sin\, \Phi\,]} + 1} \tag{21}$$

And

$$a' = \frac{1}{\frac{4F\; sin\, \Phi cos\, \Phi}{\sigma(C_L\; sin\, \Phi - C_D sin\, \Phi)} - 1} \tag{22}$$

The differential thrust coefficient dC_T , the differential torque coefficient dC_Q and the differential power coefficient dC_p, then can be defined as:

$$dC_T = \frac{dT_{BET}}{\frac{1}{2}\rho U_\infty^2 A} = \frac{\frac{1}{2}\rho U_{eff}^2\, c_r\, C_x\, N_B\, dr}{\frac{1}{2}\rho U_\infty^2\; \pi R_B^2}$$
$$dC_T = 2\frac{(1-a)^2}{\sin^2 \Phi}\, \frac{N_B\left(\frac{c_r}{R_B}\right)}{2\pi(\,r/R_B)}\, C_x d\left(\frac{r}{R_B}\right)$$

$$dC_T = 2\frac{(1-a)^2}{\sin^2 \Phi}\; \sigma C_x d\left(\frac{r}{R_B}\right) \tag{23}$$

$$dC_Q = \frac{dQ_{BET}}{\frac{1}{2}\rho U_\infty^2 A R_B} = \frac{\sigma\, \rho \frac{\left(U_\infty(1-a)\right)^2}{\sin^2 \Phi}[C_L\; sin\, \Phi - C_D sin\, \Phi\,]\pi r^2\, \Delta r}{\frac{1}{2}\rho U_\infty^2\; \pi R_B^3} = 2\frac{(1-a)^2}{\sin^2 \Phi}\; \sigma C_t\left(\frac{r}{R_B}\right) d\left(\frac{r}{R_B}\right) \tag{24}$$

And

$$dC_p = \frac{dP_{BET}}{\frac{1}{2}\rho U_\infty^3 A} = \frac{\Omega\, dQ_{BET}}{\frac{1}{2}\rho U_\infty^3 A} = 2\frac{(1-a)^2}{\sin^2 \Phi}\; \sigma C_t \Omega\left(\frac{r}{R_B}\right) d\left(\frac{r}{R_B}\right) \tag{25}$$

For a given wind turbine configuration (blade geometry and aerodynamics characteristic of the blade section), wind turbine rotational speed Ω and the wind condition (wind speed U_∞ and air density ρ), the procedure in evaluating the wind turbine performance at each blade elements can be described as follows [Hansen(13)]:

Step (1) Initialize a and a', typically a = a' = 0.
Step (2) Compute the inflow angle Φ using equation (5).
Step (3) Compute the local angle of attack using equation (6).
Step (4) Read off C_L(α) and C_D (α) from table.
Step (5) Compute C_x and C_t from equations (10b) and (10c). Step (6) Calculate a and a' from equations (21) and (22) with the tip loss factor F from equation (20).
Step (7) If a and a' has changed more than a certain tolerance, go to step (2) or else finish.
Step (8) Compute the performance of the wind turbine in term of differential thrust coefficient dC_T , differential torque dC_Q and the differential power coefficient dC_p as given by Eq. (23),(24) and Eq.(25).

Step (9) The overall power coefficient C_p can be obtained by integrating along the blade span in term of local tip speed ratio λ.

$$C_p = \frac{8}{\lambda^2}\int_{\lambda_h}^{\lambda} \lambda_r^3\, a'(1-a)\left(1-\frac{C_D}{C_L}\right)\cot \Phi \, d\lambda_r$$

3. Blade Geometry and Airfoil Characteristic Data

For the purpose of evaluating the wind turbine performance in term of power coefficient C_p for different tip speed ratio, the present work use a blade models provided by Saeed Rahgozar. S., et.al [16]. In the blade radius denoted by R_B, and the non-dimensional blade position along blade span is denoted as $\tilde{r}$, where $\tilde{r} = \frac{r}{R_B}$. Rahgozar et., al., [16] introduce three blade models, the non-dimensional chord $\widetilde{c_r}$ and the pitch angle distribution $\widetilde{\beta_r}$ along the blade span for these three blade models are given as follows:

1. Blade model - 1

Linear chord distribution : $\widetilde{c_r} = -0.16\tilde{r} + 0.2$ (26a)

Non-linear pitch distribution : $\widetilde{\beta_r} = 16.58\tilde{r}^2 - 47.62\tilde{r} + 32.47$ (26b)

2. Blade Model - 2

Non-linear chord distribution : $\widetilde{c_r} = 0.11\tilde{r}^2 - 0.32\tilde{r} + 0.26$ (27a)

Linear pitch distribution : $\widetilde{\beta_r} = -23.51\tilde{r} + 24.59$ (27b)

3. Blade Model - 3

Non-linear chord distribution : $\widetilde{c_r} = 0.2\tilde{r}^2 - 0.4\tilde{r} + 0.26$ (28a)

Non-linear pitch distribution : $\widetilde{\beta_r} = 33.71\tilde{r}^2 - 63.81\tilde{r} + 35.24$ (28b)

Fig. 3 show graphical comparison these three blade models for the chord distribution while Fig. 4 for the pitch distribution along the blade span.

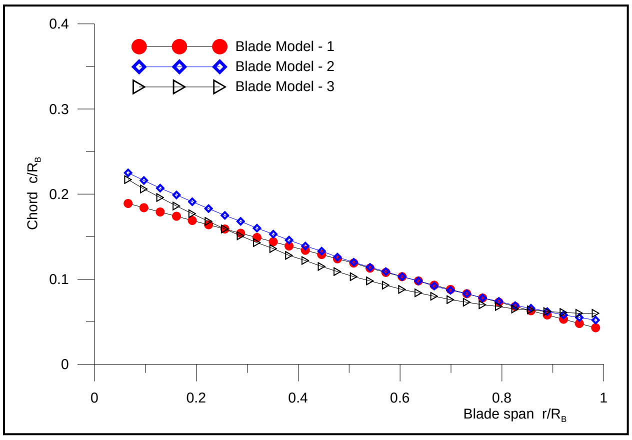

Fig. 3 - Chord distribution along blade span

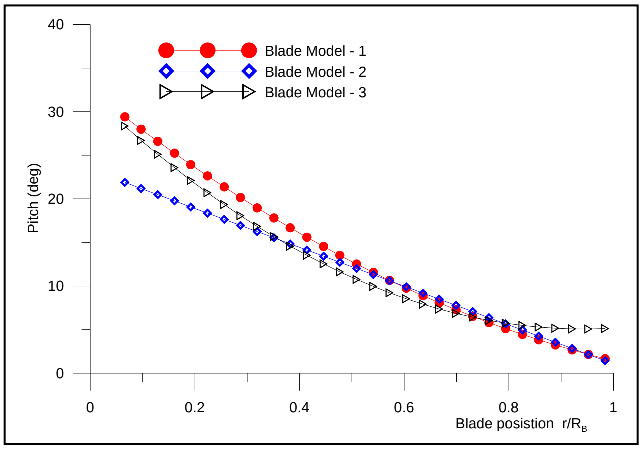

Fig. 4 - Pitch distribution along blade span

Here the blade assumed to have airfoil section NACA 0012,
In which the lift coefficient C_ℓ and C_d as function of angle of attack α and Reynolds number R_e are given as[17]:

$$C_\ell(\alpha) = \begin{cases} -12.0\left(0.1025 + 0.00485\log\frac{R_e}{10^6}\right) & \text{for } \alpha \leq -12^0 \\ \alpha\left(0.1025 + 0.00485\log\frac{R_e}{10^6}\right) & \text{for } -12 < \alpha < 12^0 = \\ 12.0\left(0.1025 + 0.00485\log\frac{R_e}{10^6}\right) & \text{for } \alpha \geq 12^0 \end{cases} \tag{29a}$$

And

$$C_\ell(\alpha) = 0.0044 + 0.018R_e^{-0.15} + 0.009\left(\frac{C_\ell(\alpha)}{1.2}\right)^2 \tag{29b}$$

4. Discussion and Result

As mentioned in previous sub chapter, the wind turbine performance involves in determining three performance parameters, namely the thrust coefficient C_T, torque coefficient C_Q, and the power coefficient C_P. The Blade Element Momentum theory allows one to estimate these three coefficient along blade span as given by Eq. (23) to Eq.(25). These three equations are derived from the Blade Element Theory, an attempt to use the formulation derived from the Momentum theory it is found does not work. Using data geometry blade and airfoil as described in sub chapter 3, the comparison result between these three blade model in term of thrust coefficient thrust coefficient C_T, torque coefficient C_Q, and the power coefficient C_P along blade span for two bladed wind turbine operated at the tip speed ratio λ = 5 , wind speed $U_\infty = 10\frac{m}{sec}$ and the blade radius $R_B = 1.8\,m$. The last two data are required since the aerodynamics characteristic of the airfoil section is presented as a function of Reynolds number R_e beside the angle of attack α.

Fig. 5 shows a comparison result of the thrust coefficient along blade span these three blade models. Blade model-1 having a non linear chord distribution and a linear twist distribution has a higher value compared with the other two.

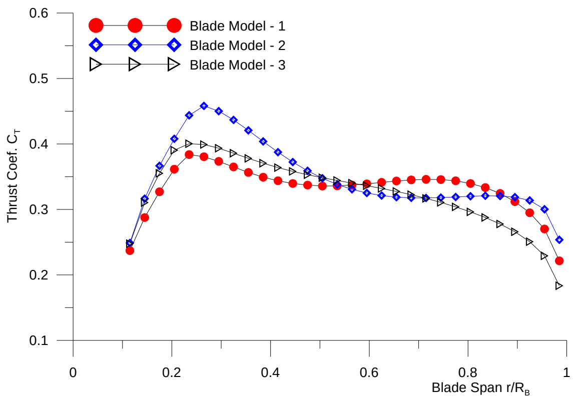

Fig. 5 - Distribution of Thrust Coefficient C_T along blade span

In term of torque coefficient distribution along blade span as shown in the Fig. 6. This Figure shows that in term of torque coefficient blade model – 2 offer a better torque compared with two others. Second blade model has a non-linear chord accompanied with a linear pitch distribution.

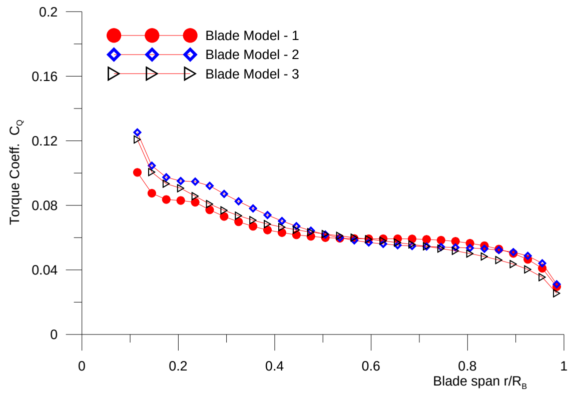

Fig. 6 - Distribution of Torque Coefficient C_Q along blade span

While in view of power coefficient C_p has the same shape of C_Q-curve, since C_p is equal to the tip speed ratio λ multiply by C_Q. The comparison result of C_p along blade span for these three blade model as shown in the Fig. 7.

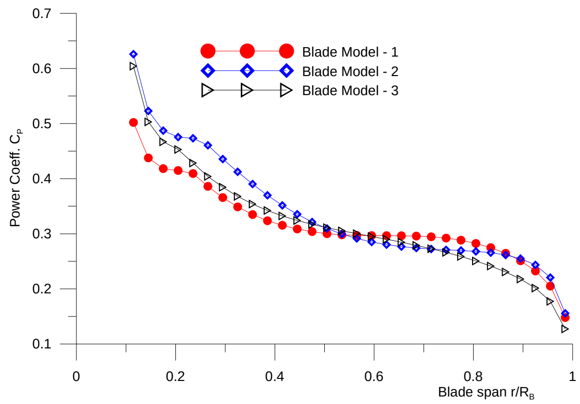

Fig. 7 - Distribution of power Coefficient C_P along blade span

The wind turbine performance for various tip speed ratio λ for the thrust coefficient as shown in the Fig. 8.

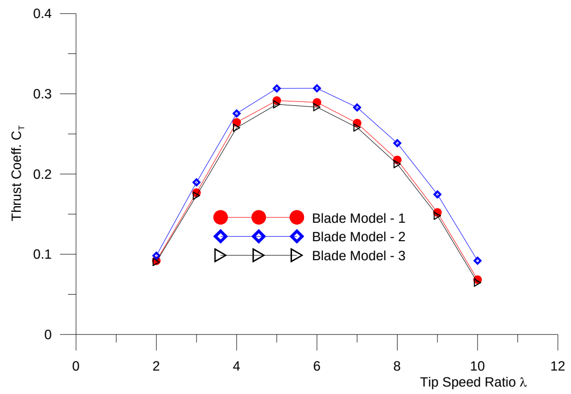

Fig. 8 - The Thrust Coefficient C_T versus tip speed ratio λ

While in term of torque coefficient and power coefficient their comparison between three blade geometry models are shown in the Fig. 9 and Fig. 10 respectively.

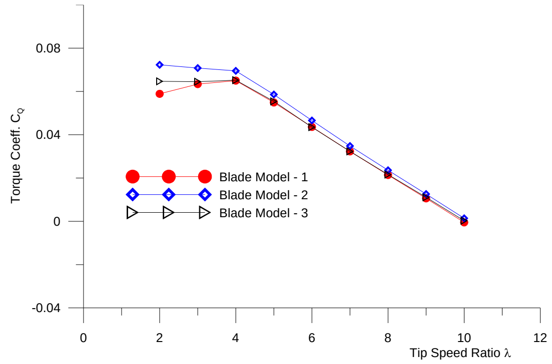

Fig. 9 - The Torque Coefficient C_Q versus tip speed ratio λ

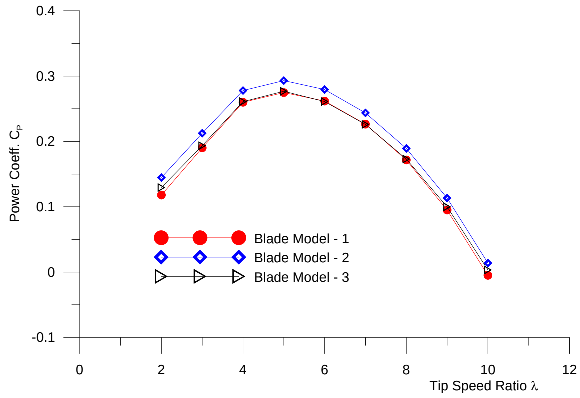

Fig. 10 - The Power Coefficient C_P versus tip speed ratio λ

Considering the result of power coefficient C_p as shown in the Fig. 10, the result of blade model – 1 is nearly the same as blade model-3. These two blade use a non-linear pitch while the blade model – 2 use a linear pitch distribution, which give a higher power coefficient than two others blade models.

5. Conclusion and Future Work

Considering the result as shown in Discussion and Result shows that the Blade Element Momentum Theory with the procedure as described by Hansen[13] is work able. This approach can be applied to the blade geometry having shape as typical of model blade as given by Rahgozar. S[15]. It is suggested that in the future works are carried out for different blade geometry as well as different airfoil.

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