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The Improvement of Blade Element Momentum Theory in Horizontal Axis Wind Turbine Performance Analysis

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Abstract: The present work uses the blade element momentum theory method for evaluating the performance of horizontal axis wind turbine. The wind turbine performances are described in term of the thrust coefficient C_T, torque coefficient C_Q and the power coefficient C_P. The blade element momentum theory (BEMT) represents the wind turbine performance prediction method as result of combining two methods, namely the blade element theory (BET) and the momentum theory (MT). Both theories are able to formulate the axial forces and torques which work on the blade. Equating axial force and torque formulated by BET is equal axial force and torque by MT, makes one allows the axial induction factor and the angular induction factor a^', the unknown quantities, can be defined and furthermore the wind turbine performances can be evaluated. The BEMT method used here is the combination of BEMT. The implementation this method as the tool for predicting the wind turbine performances are work well. However, for wind turbine configuration need a little adjustment, especially in setting the hub radius r_h where the blade element momentum theory starts to make calculation from the inner blade to the tip. The high pitch angle and a relatively a large chord length at r_h, make the BEMT fail to converge. In addition to the present work found that the three wind turbine performance coefficients are formulated by using the momentum theory is less accurate compared with BET formulation.

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

1. Introduction

There is various method had been introduced as the design and analysis of the horizontal axis wind turbine (HAWT), such as the Blade element theory [1], The momentum Theory [2], The Prescribed wake method [3], The free wake Method [4] or various method that can be derived from the use of CFD [5.6]. It is true that currently the CFD plays an important role in aerospace industries. The present computer capability and better understanding in developing numerical method for solving the governing equation of fluid motion, allow the flow problem over full aircraft configurations are solved by use a Time Averaged Navier Stokes equation [7,8]. A similar approach is also used for solving rotor blade helicopter [9,10] and also for the wind turbines [11]. Although there are various methods that have already been developed, the Blade Element Momentum Theory may represent a preferred method to be used in designing wind turbines. This method allows one to obtain the overall wind turbine performance faster. Basically, the blade element momentum theory represents the combining two methods, the blade element theory and the momentum theory. The blade element momentum theory mainly is the combination between the blade theory and momentum theory. The blade element theory assumes that the turbine blade consists from a number of elements, that elements can be treated independently as two-dimensional airfoils. The aerodynamics characters at each section can be easily defined if the effective velocity at each section is known. In the momentum theory, the flow pass through rotor blade divided into two region, undisturbed and disturbed flow region. The disturbed flow region has the form as stream tube with circular cross section. At the rotor blade, the cross section is twice the turbine blade radius. The diameter of the cross section increases as the flow goes

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further downstream, while in the upstream part, the cross section is decreasing. Similar to the blade element theory, these two methods are able to formulate the axial force and torque in terms of axial induced velocity and angular induced wind speed. Both induced velocities represent unknown quantities, if these velocities can be obtained the wind turbine performance can be deduced. By quoting the forces and torque defined by the blade element theory and by the momentum theory makes the two induced velocities can be defined. Subsequently the wind turbine performances are stated in terms of thrust coefficient C_T, torque coefficient C_Q and the power coefficient C_P can be determined. The blade element momentum theory used in the present work represents the blade element momentum theory adopted from Hansen [12], Wood [13] and Moriarty et.al [14]. This paper aims to investigate the ability of blade element momentum theory to predict the performance of horizontal axis wind turbine, starting from the basic approach as suggested by Hansen to gradually improved by adding correction factors and a proper input for the required aerodynamics characteristics airfoil. The wind turbine used in this present work is the wind turbine with the blade geometry used the blade as suggested by Rahgozar et al. [15].

2. The Blade Element Momentum Theory

The blade element momentum theory represents the method for evaluating the performance of wind turbine through combining the blade element theory and the momentum theory. As result of the interaction between the incoming free stream (wind), the rotating blade and extracting wind kinetic energy makes the flow cross the blade experiences a reducing velocity in the axial direction and increasing the tangential velocity in rotational plane direction. Let's the incoming wind speed and the wind turbine angular velocity denoted by V_w and Ω respectively. While the axial and angular induction factor are denoted as a and a''. As the blade cross section has a form as an airfoil. One can describe the velocity and force diagram at any blade section. Fig. 1 shows the velocities and force diagram for the blade section located at a distance r from the axis rotation.

Fig. 1 shows the blade cross section with respect to the plane of rotation has a pith angle β, the inflow angle Φ and the angle of attack α. If the axial and angular induction factor a and a' are known, the effective velocity V_{eff} and the angle of attack α can be defined. As result the aerodynamics forces in the axial adF_x and tangential direction dF_t over the blade segment dr can be formulated .

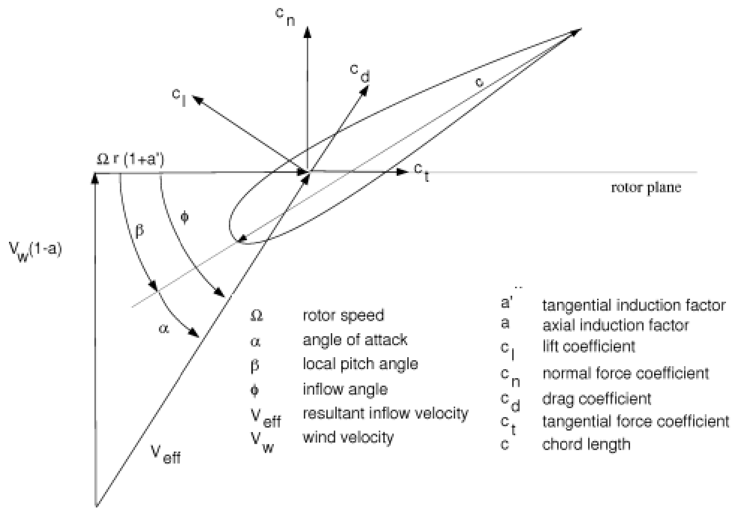

Fig. 1 - Velocities and forces at the blade section

For N_B bladed horizontal axis wind turbine, the differential axial force dF_x and tangential force dF_t from the point of view the Blade Element Theory can be defined as Hansen [12]:

$$dF_x = \frac{1}{2}\rho U_{eff}^2\, c_r\, C_x\, N_B\, dr \tag{1}$$

$$dF_t = \frac{1}{2}\rho U_{eff}^2\, c_r\, C_t\, N_B\, dr \tag{2}$$

Where:

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

$$U_{eff}^2 = U_w^2\left(\left(1-a\right)\right)^2 + \left(\lambda_r(1+a')\right)^2 \tag{3}$$

$$C_x = C_L \cos \Phi + C_D \sin \Phi \tag{4}$$

$$C_t = C_L \sin \Phi - C_D \cos \Phi \tag{5}$$

$$\Phi = arctg\left(\frac{U_x}{U_t}\right) = arctg\left(\frac{U_\infty(1-a)}{\Omega r(1+a')}\right) \tag{6}$$

$$\alpha = \Phi - \beta \tag{7}$$

c_r : local chord length
ρ : air density
$\lambda_r = \left(\frac{r}{R_B}\right)\lambda$
$\lambda = \dfrac{\Omega R_B}{U_w}$

This differential tangential force dF_t generates a differential torque dQ as

$$dQ = r\, dF_t = \frac{1}{2}\rho U_{eff}^2\, c_r\, C_t\, N_B\, r\, dr \tag{8}$$

From the point of view the Momentum theory, for given axial and angular induction factor a and a' one can derive that dF_{xM} and the differential torque dQ_M are given respectively as[12]

$$dF_M = \rho V_w^2\, 4a\,(1-a)\,\pi r\, dr \tag{9}$$

And

$$dQ_M = \rho V_w\, 4a'\,(1-a)\,\pi r^3\, \Omega dr \tag{10}$$

By setting Eq.(1) is equal to Eq.(9) and the Eq.(8) is equal with Eq.(10), one has two equations with a and a' are as the unknown quantities. Namely

$$dF_x = dF_M$$

$$\frac{1}{2}\rho U_{eff}^2\, c_r\, C_x\, N_B\, dr = \rho V_w^2\, 4a\,(1-a)\,\pi r\, dr$$

Or

$$a = \frac{1}{\frac{4\sin^2\Phi}{\sigma[C_L \cos\Phi + C_D \sin\Phi]}+1} \tag{11}$$

And

$$r\, dF_t = dQ_M$$

$$r\left[\frac{1}{2}\rho U_{eff}^2\, c_r\, C_t\, N_B\, dr\right] = \rho V_w\, 4a'\,(1-a)\,\pi r^3\, \Omega dr$$

Or

$$a' = \frac{1}{\frac{4\sin\Phi\cos\Phi}{\sigma(C_L \sin\Phi - C_D\cos\Phi)}-1} \tag{12}$$

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

The axial induction factor a as well as the angular induction factor a' can be solved from Eq. (11) and Eq. (12) using an iteration process. one can obtain the value of If the axial induction factor a as well as the angular induction factor a', the wind turbine performances at each blade segment located at a distance r from the axis rotation can be obtained, as follows:

The local thrust coefficient $C_T(r)$

$$C_T(r) = \frac{dF_x}{\frac{1}{2}\rho V_w^2 dA} = \frac{\frac{1}{2}\rho V_{eff}^2 \, c_r \, C_x \, N_B \, dr}{\frac{1}{2}\rho V_w^2 \, 2\pi r \, dr}$$

$$C_T(r) = 2\frac{(1-a)^2}{\sin^2 \Phi} \, \sigma C_x d\left(\frac{r}{R_B}\right) \tag{14}$$

Differential torque coefficient

$$C_Q(r) = \frac{dQ_{BET}}{\frac{1}{2}\rho V_w^2 \, dA \, r}$$

$$= \frac{\sigma \, \rho \frac{\left(U_W(1-a)\right)^2}{\sin^2 \Phi}[C_L \, sin \, \Phi - C_D sin \, \Phi \,]\pi r^2 \, dr}{\frac{1}{2}\rho V_w^2 \, 2\pi r^2 \, dr}$$

$$= 2\frac{(1-a)^2}{\sin^2 \Phi} \, \sigma C_t \left(\frac{r}{R_B}\right) \tag{15}$$

Differential power coefficients

$$C_p(r) = \frac{dP_{BET}}{\frac{1}{2}\rho U_\infty^3 dA} = \frac{\Omega \, dQ_{BET}}{\frac{1}{2}\rho U_\infty^3 dA}$$

$$= 2\frac{(1-a)^2}{\sin^2 \Phi} \, \sigma C_t \Omega\left(\frac{r}{R_B}\right) \tag{16}$$

To estimate the wind turbine performance the following data has to be provided are:

- The blade number N_B,
- The blade geometry $\left(\text{chord} \;\; c(r), \; \text{pitch} \; \beta(r)\right)$
- The aerodynamic characteristics of airfoil: lift and drag coefficient as function angle of attack $\left(C_\ell(\alpha) \text{ and } C_d(\alpha)\right)$,
- The blade radius R_B,
- Tip speed ratio λ and
- wind speed V_w

If above required data are available, the wind turbine performance can be carried out, by firstly one solves Eq. (11) and (12) to obtain the axial and angular induction factor a and a' . Unfortunately, these equations are non-linear, hence iteration process is required. Strictly speaking, the procedure in predicting the wind turbine performance by using the blade element momentum theory adopted from Hansen [12] can be described as follows:

Step (1) Initialize a and a', typically a = a' = 0.
Step (2) Compute the inflow angle Φ using equation (6).
Step (3) Compute the local angle of attack using equation (7).
Step (4) Read off $C_L(\alpha)$ and $C_D(\alpha)$ from table.
Step (5) Compute C_x and C_t from equations (4) and (5).
Step (6) Calculate a and a'from equations (11) and (12)
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 C_T , differential torque C_Q and the differential power coefficient C_p as given by Eq. (14), (15) and Eq. (16).
Step (9) The overall power coefficient C_p can be obtained by integrating along the blade span. The simple method for numerical integration one may use a Trapezoidal Rule [16]

3. The Improvement on the Blade Element Momentum Theory

The Blade element as described in the previous chapter is only valid for rotors with infinite many blades. In order to correct for finite number of blades, Prandtl introduced tip loss factor to correct the loading. As result the axial and angular induction factor to accommodate the presence of tip losses become:

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

And

$$a' = \frac{1}{\frac{4F\ \sin\Phi\cos\Phi}{\sigma(C_L\ \sin\Phi - C_D \sin\Phi)}-1} \tag{18}$$

Where the tip loss factor F is defined as:

$$F = \frac{2}{\pi}\cos^{-1}\left(e^{-\frac{N_B}{2}\left(\frac{R_B-r}{r\sin\Phi}\right)}\right) \tag{19}$$

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

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

In the case that the axial induction factor a is greater than about 0.4, makes the flow entrains from outside the wake and the turbulence increases. As result the flow behind the rotor slows down, but the thrust on the rotor disk continues to increase. To compensate for this effect, Buhl [14] modify the tip loss factor F to become a loss factor F which include the tip-hub loss correction in the form:

$$F = F_{tip}\ F_{hub} \tag{23}$$

Where F_{tip} as defined by Eq.(20), while F_{hub} has the form as:

$$F_{hub} = \frac{2}{\pi}\cos^{-1}\left(e^{-\frac{N_B}{2}\left(\frac{R_B-hub}{r\sin\Phi}\right)}\right) \tag{19}$$

In this context, the thrust coefficient C_T needs to be calculated by using the following relations:

$$C_T = \begin{cases} 4aF(1-a) & for\ \ a \le 0.2 \\ 4aF(0.04+0.6a) & for\ \ a > 0.2 \end{cases} \tag{20}$$

The axial induction factar a is, then, calculated by :

$$a = 1 + 0.5(0.6K - 0.5\sqrt{(0.6K+2)^2 + 4(0.04K-1.0)} \tag{21}$$

Where:

$$K = \frac{4F\sin^2\Phi}{\sigma C_x} \tag{22}$$

If the aixial induction factor a is found greater than 0.33, the manner how the thrust coefficient C_T is determined by Eq. (14), or (20) needs to be replaced by the following equations [15]:

$$C_T = 4\, aF\left(100.25a(5-3a)\right) \tag{23}$$

In addition, the improvement of the BEMT through introduction the tip loss factor as well as the hub loss factor, the BEMT improvement can also be carried by improvement on the aerodynamics characteristics airfoil in use. Previously the wind turbine blades were designed using well-tested aviation airfoils, such as the NACA 44xx and the NACA 63-4xx airfoils. The aerodynamics data for these kinds of airfoil mostly are available and obtained from the wind tunnel test. These aerodynamics characteristics airfoil data can be obtained from Abbott and von Doenhoff [16]. These data are purely two-dimensional aerodynamics data, while the blade of wind turbine is three-dimensional configuration and acts as a rotating blade, Here Viterna and Corrigan [17] introduce the formulation of aerodynamics characteristics of airfoil of infinity span to become aerodynamics characteristics of finite blade span.

For the case of angle of attack below stall angle α_s , the aerodynamics characteristic of a finite wing airfoil [17]:

$$C_L = C_{L0} \tag{24a}$$

$$C_L = C_{D0} + \frac{C_L^2}{\pi A_R} \tag{24b}$$

$$\alpha = \alpha_0 + \frac{57.3\, C_L}{\pi A_R} \tag{24c}$$

In above equation A_R is aspect ratio and subscript 0 is used that the corresponding quantities is the quantity at infinite wing span. If the angle of attack α greater than stall angle α_s, the aerodynamics characteristic airfoil becomes:

$$C_L = \frac{1}{2} C_{Dmax} \sin 2\alpha + A_2 \frac{\cos^2\alpha}{\sin\alpha} \tag{25a}$$

$$C_D = \frac{1}{2} C_{Dmax} \sin^2\alpha + B_2 \cos\alpha \tag{25b}$$

Where :

$$A_2 = \frac{1}{2}\left(C_{L,s} - C_{Dmax}\sin\alpha_s\ \cos\alpha_s\right)\frac{\sin\alpha}{\cos^2\alpha} \tag{26a}$$

$$B_2 = \frac{1}{2}\left(C_{D,s} - C_{Dmax}\sin^2\alpha_s\right)\frac{1}{\cos\alpha_s} \tag{26b}$$

$$C_{Dmax} = \begin{cases} 1.11 + 0{,}018\, A_R \ \ for\ A_R < 50 \\ 2 \quad for\ A_R \geq 50 \end{cases} \tag{3,6b}$$

The blade aspect ratio A_R here can be defined as:

$$A_R = \frac{R_B^2}{S} = \frac{R_B^2}{\int_{r_h}^{R_B} c\, dr} \tag{26c}$$

4. 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 uses 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 both are a nonlinear models defined as:

$$\text{chord distribution}: \widetilde{c_r} = 0.2\tilde{r}^2 - 0.4\tilde{r} + 0.26 \tag{28a}$$

$$\text{pitch distribution}: \widetilde{\beta_r} = 33.71\tilde{r}^2 - 63.81\tilde{r} + 35.24 \tag{28b}$$

The required airfoil;s aerodynamics characteristics use the airfoil provided by XLFR5 computer which already available airfoil tools website [18]. For NACA 4415 at Reynolds number $R_e = 500\ 000$, the aerodynamics characteristics of the airfoil is given in the Table 1 bellows.

Table 1 Aerodynamics characteristics airfoil NACA 4415

Alpha	C_L	C_D	Alpha	C_L	C_D
-16.50	-0.820	0.081	0.25	0.433	0.007
-16.25	-0.847	0.075	0.50	0.454	0.007
-16.00	-0.882	0.067	0.75	0.472	0.007
-15.75	-0.919	0.060	1.00	0.489	0.007
-15.50	-0.963	0.051	1.25	0.505	0.007
-15.25	-1.003	0.043	1.50	0.521	0.007
-15.00	-1.036	0.036	1.75	0.534	0.007
-14.75	-1.030	0.032	2.00	0.648	0.007
-14.50	-1.018	0.029	2.25	0.715	0.007
-14.25	-1.005	0.027	2.50	0.749	0.007
-14.00	-0.992	0.026	2.75	0.782	0.007
-13.75	-0.973	0.025	3.00	0.821	0.008
-13.50	-0.951	0.024	3.25	0.861	0.008
-13.25	-0.925	0.023	3.50	0.903	0.008
-13.00	-0.910	0.022	3.75	0.941	0.008
-12.75	-0.884	0.021	4.00	0.957	0.008
-12.50	-0.860	0.020	4.25	0.976	0.008
-12.25	-0.832	0.019	4.50	0.993	0.008
-12.00	-0.812	0.018	4.75	1.011	0.008
-11.75	-0.788	0.018	5.00	1.027	0.009
-11.50	-0.759	0.017	5.25	1.042	0.009
-11.25	-0.729	0.016	5.50	1.058	0.009
-11.00	-0.697	0.016	5.75	1.073	0.009
-10.75	-0.666	0.015	6.00	1.090	0.009
-10.50	-0.647	0.015	6.25	1.106	0.009
-10.25	-0.616	0.014	6.50	1.123	0.010
-10.00	-0.581	0.014	6.75	1.140	0.010
-9.75	-0.546	0.013	7.00	1.157	0.010
-9.50	-0.520	0.013	7.25	1.175	0.010
-9.25	-0.491	0.012	7.50	1.191	0.010
-9.00	-0.456	0.012	7.75	1.207	0.011
-8.75	-0.432	0.011	8.00	1.224	0.011
-8.50	-0.403	0.011	8.25	1.239	0.011
-8.25	-0.375	0.011	8.50	1.254	0.012
-8.00	-0.350	0.010	8.75	1.267	0.012
-7.75	-0.322	0.010	9.00	1.282	0.013
-7.50	-0.299	0.010	9.25	1.296	0.013
-7.25	-0.273	0.010	9.50	1.310	0.014
-7.00	-0.250	0.009	9.75	1.324	0.014
-6.75	-0.224	0.009	10.00	1.337	0.015
-6.50	-0.200	0.009	10.25	1.352	0.015
-6.25	-0.174	0.009	10.50	1.365	0.016
-6.00	-0.151	0.009	10.75	1.379	0.017
-5.75	-0.126	0.009	11.00	1.393	0.017
-5.50	-0.102	0.009	11.25	1.405	0.018
-5.25	-0.077	0.008	11.50	1.419	0.018
-5.00	-0.053	0.008	11.75	1.432	0.019
-4.75	-0.029	0.008	12.00	1.443	0.020

-4.50	-0.005	0.008	12.25	1.457	0.021
-4.25	0.019	0.008	12.50	1.468	0.022
-4.00	0.043	0.008	12.75	1.480	0.023
-3.75	0.067	0.008	13.00	1.491	0.023
-3.50	0.091	0.008	13.25	1.500	0.025
-3.25	0.114	0.008	13.50	1.510	0.026
-3.00	0.138	0.008	13.75	1.517	0.027
-2.50	0.184	0.008	14.00	1.523	0.028
-2.25	0.207	0.008	14.25	1.529	0.030
-1.75	0.254	0.008	14.50	1.532	0.032
-1.50	0.276	0.008	14.75	1.534	0.034
-1.25	0.300	0.008	15.00	1.537	0.035
-1.00	0.323	0.008	15.25	1.538	0.038
-0.75	0.345	0.007	15.50	1.540	0.040
-0.50	0.368	0.007	15.75	1.540	0.042
-0.25	0.390	0.007	16.00	1.542	0.044
0.00	0.413	0.007	16.25	1.541	0.047

5. Results and Discussion

In the context no tip loss effects, the wind turbine performance analysis is carried to the case of wind turbine operated under wind speed $V_w = 10\ \frac{m}{sec}$. The airfoil section is the NACA 0012 with its aerodynamics characteristics of lift coefficient C_ℓ and C_d as function of angle of attack α and the Reynolds number follows the formulation of Wood [18]. The comparison results for different blade number in the case of blade geometry as defined by Eq. (28) in term of thrust coefficient C_T and the power coefficient C_T as shown in the Fig. 2 and Fig. 3 respectively. It is necessary to be noted, these results are obtained with no tip losses included in the wind turbine performance analysis. Unfortunately, above BEMT implementation as describing in 9 steps, need adjustment in introducing distance r_h. For the case of blade number $N_B = 2,$ the hub radius r_h can be set equal to $0.1 R_B$ while other need to be set $r_h = 0.15\ R_B$

While the comparison result between with and with out tip losses factor to the case of four bladed wind turbine in term of thrust coefficient C_T and the power coefficient C_P as shown in the Fig. 4 and Fig. 5 respectively.

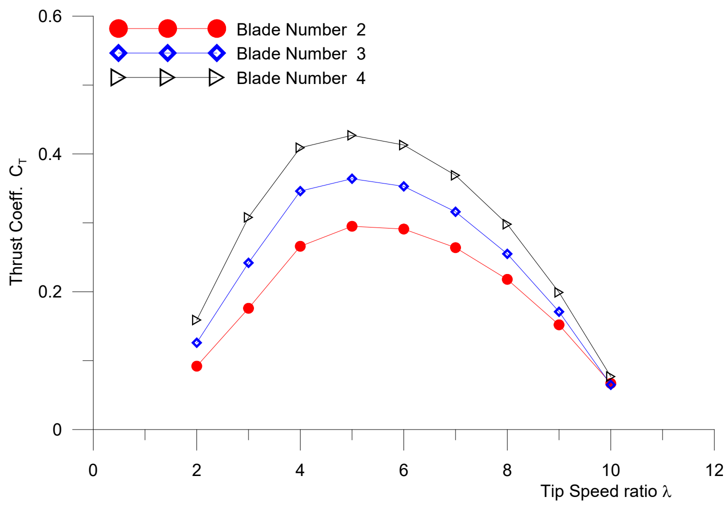

Fig. 2 - The thrust coefficient C_T as function of tip speed ratio λ for different of blade number

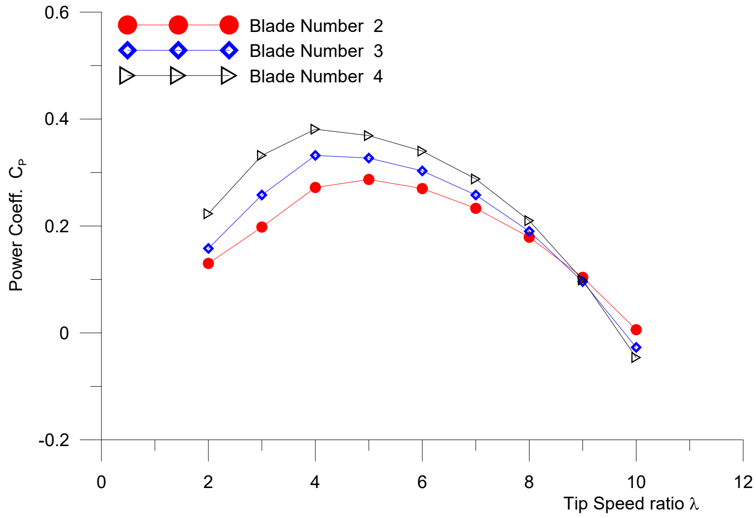

Fig. 3 The thrust coefficient C_p as function of tip speed ratio λ for different of blade number

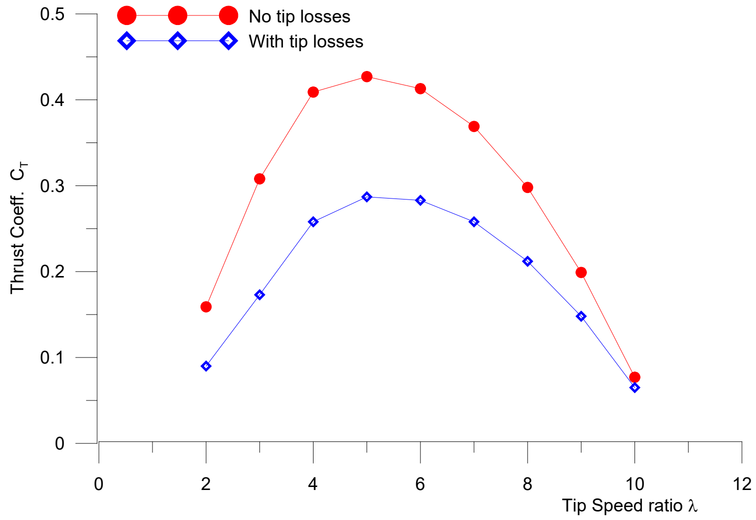

Fig. 4 - The thrust coefficient C_T as function of tip speed ratio λ with and without tip losses

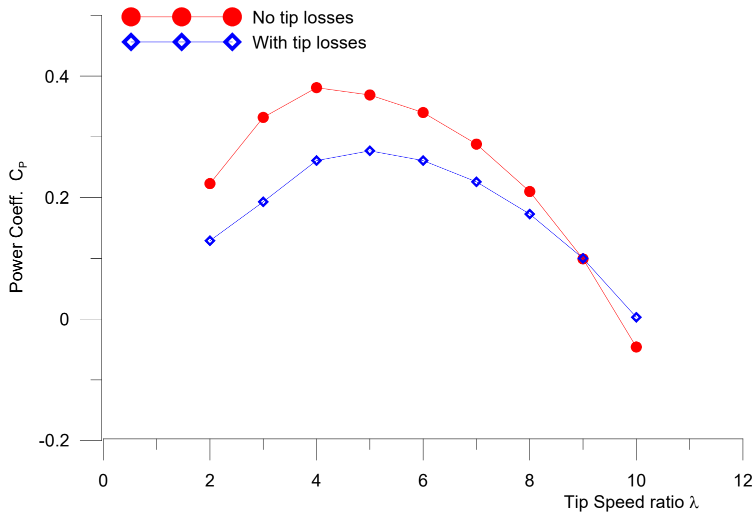

Fig. 5 - The power coefficient C_P as function of tip speed ratio λ with and without tip losses

The following test case is the problem with blade section has an airfoil NACA 4415. The wind turbine performance is carried out by including the tip loss factor for different number of blade. The result in term of thrust coefficient C_T and the power coefficient C_P as shown in the Fig. 6 and Fig. 7 respectively.

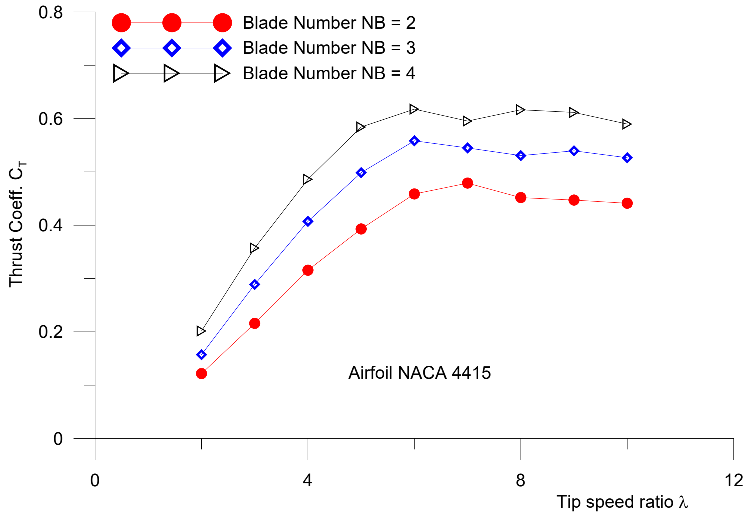

Fig. 6 - The thrust coefficient C_T as function of tip speed ratio λ with tip losses for different blade number

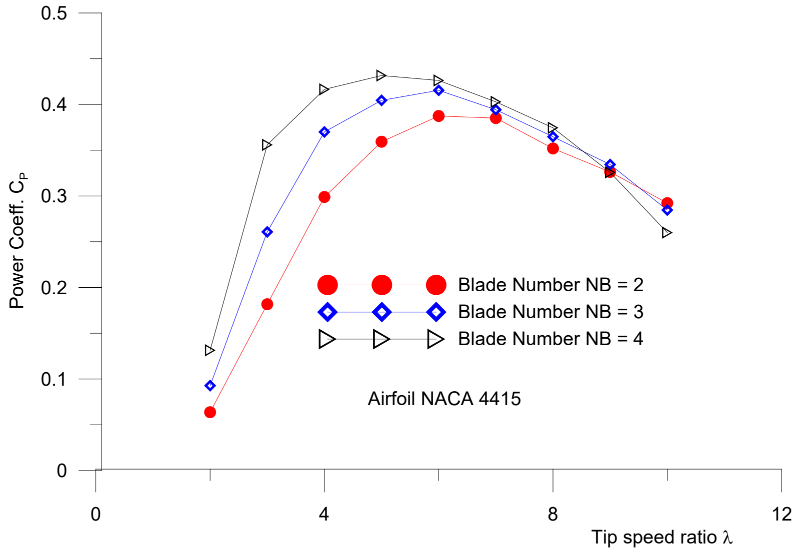

Fig. 7 - The power coefficient C_P as function of tip speed ratio λ with tip losses for different blade number

6. Conclusion

In conclusion, the blade element momentum theory with the procedure as described by Hansen[15] is work able. This approach can be applied to the blade geometry having shape as typical of model blade as given by Rahgozar. S[16]. It is suggested that in the future works are carried out for different blade geometry as well as different airfoil.

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