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Tip loss factor effects on aerodynamic performances of horizontal axis wind turbine

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Abstract

Tip loss corrections are an important factor in Blade Element Momentum (BEM) theory when determining optimum blade design for maximum power production. This paper presents the optimal tip design using the new tip loss correction. A semi-analytical solution was proposed to find the optimum rotor considering Shen's new tip loss model. The optimal blade geometry is obtained for which the maximum power coefficient is calculated at different design tip speed and glide ratio. Our simulation is conducted for S809 rotor wind turbine blade type, produced by National Renewable Energy Laboratory (NREL).

Keywords: BEM method, S809 airfoil, Horizontal axis wind turbine, Aerodynamic performances, Tip speed ratio, power coefficient

1. Introduction

The design of wind turbines rotor was made by computational codes must be able to gives the best wind turbine geometry in order to obtain the maximum power. Computational fluid dynamic code (CFD) is widely used, to produce the accurate results, but on the other need longer time for calculation and big informatics memory. The mathematical model most frequently used by industrial and scientific research, this code based on Blade Element Momentum Theory (BEMT), it gives less accurate results, but it is possible to determine the optimal rotor geometry with maximum power design and evaluate the forces and torque acting on the blades. The optimal design of blade geometry is based on several parameters. Whilst Navier-Stokes solvers can be incorporated into rotor optimization for greater accuracy, BEM computations have significant advantages in computational speed and ease of implementation. An alternative to using a more computationally intensive method is to modify the BEM model and

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apply corrections to the technique. One of the most important corrections to BEM analysis is a tip loss correction. The concept of a tip loss was introduced by Prandtl [1] to simplify the wake of the turbine by modeling the helical vortex wake pattern as vortex sheets that are convected by the mean flow and have no direct effect on the wake itself. This theory is induced velocity field, F. This correction is used to modify the momentum of the blade element momentum equations. One lilitation of this model is that it assumes the wake does not expand, limiting its validity to lightly loaded rotors.

Another limitation of the BEM theory is that when the axial induction factor is greater than 0.4, the basic theory becomes invalid. This occurs with turbines operating at high tip speed ratio, for this Glauert [2] developed a correction to the trust coefficient based on experimental measurements with large induced velocities. While this model was originally developed as a correction to the thrust coefficient of a rotor, it has also been used to correct the local coefficient of the individual blade elements when used with BEM theory. Because of this, it is important to understand the Glauert correction's relationship to the tip-loss model. When the losses near the tip are high, the induced velocities are large; therefore, the possibility of a turbulent wake near the tips increases. Thus, for each element the total induced velocity calculation must use a combination of the tip-loss and Glauert corrections. A new modification derived by [3] to the Glauert empirical relation that included a new formulation of the tip-loss correction. Shen et al. [4] corrected both the induced velocities and the mass flux for tip loss effects, and corrected the lift coefficient by introducing a new factor. Others corrections introduced by [5-7] for BEMT solver for two such phenomena: tip-hub loss factor and high induction factor conditions.

The objective of the current work is to maximise the power extraction efficiency of a wind turbine rotor, with a focus on the effect of various tip loss models on the optimal rotor shape and introduce a new formulation of axial and angular induction factors.

2. Mathematical model

As the classical theory of wind turbine rotor aerodynamic, the BEM method combines the momentum and blade element theory. The blade is divided into several elements, by applying the equations of momentum and angular momentum conservation, for each element dr section of the blade, axial force and torque can be defined by Eqs. (1) and (2), respectively:

$$dT = \frac{1}{2} B\rho c V_{rel}^2 C_n dr \tag{1}$$

$$dM = \frac{1}{2} B\rho c V_{rel}^2 C_t r dr \tag{2}$$

These relations from the momentum theory alone do not include the effects of blade shape, for it, the blade element theory was introduced. Accordingly, the angle of relative wind, ϕ and twist angle is determined by Eqs. (4) and (5) respectively:

$$\tan(\phi) = \frac{(1-a)V_0}{(1+b)\Omega r} \tag{4}$$

$$\beta = \phi - \alpha_{op} \tag{5}$$

Where α_{op}, is the optimal angle of attack, it extracted from 2D CFD calculation.

The turbine has B number of blades. Therefore, the force of thrust and torque at each element *dr* given by Eq. (6) and (7) respectively:

$$dT = 4\pi B\rho V_0^2 a(1-a) r dr \tag{6}$$

$$dM = 4\pi B\rho V_0 \Omega b(1-a) r^3 dr \tag{7}$$

By equating (1) with (6) and (2) with (7), the axial and tangential induction factors can be found as follows:

$$a = \frac{\sigma C_n}{4\sin^2\phi + \sigma C_n} \tag{8}$$

$$b = \frac{\sigma C_t}{4\sin\phi\cos\phi - \sigma C_t} \tag{9}$$

2.1. Prandtl's Loss Factor correction

The above equations are 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. This factor derived in Eqs. (6) and (7), the incremental thrust force and torque to be modified by:

$$dT = 4\pi BF\rho V_0^2 a(1-a) r dr \tag{10}$$

$$dM = 4\pi BF\rho V_0 \Omega b(1-a) r^3 dr \tag{11}$$

The tip loss factor, F, defined by Eq. (13).

$$F_{tip} = \frac{2}{\pi}\arccos\left[\exp\left(\frac{-B(R-r)}{2r\sin\phi}\right)\right] \tag{12}$$

After considering tip loss factor, Eqs. (8) and (9) should be changed to:

$$a = \frac{\sigma C_n}{4F\sin^2\phi + \sigma C_n} \tag{13}$$

$$b = \frac{\sigma C_t}{4F\sin\phi\cos\phi - \sigma C_t} \tag{14}$$

And thrust coefficient is defined by Eq. (15):

$$C_T = 4aF(1-a) \tag{15}$$

2.2. Glauert and De Vries corrections

Another limitation of the BEM theory is that when the induction factor is greater than about 0.4, the basic theory becomes invalid. Physically, the flow entrains from outside the wake and the turbulence increases. The flow behind the rotor slows down, but the thrust on the rotor disk continues to increase. To compensate for this effect, Glauert developed a correction to the rotor thrust coefficient based on experimental measurements of helicopter rotors with large induced velocities. Thus, for each element the total induced velocity calculation must use a combination of the tip-hub loss and Glauert corrections. Buhl derived a modification to the Glauert empirical relation that included the tip-hub loss correction as follows:

$$F = F_{tip} * F_{hub} \tag{16}$$

Where

$$F_{tip} = \frac{2}{\pi}\arccos\left[\exp\left(\frac{-B(R-r)}{2r\sin\phi}\right)\right] \text{ and } F_{hub} = \frac{2}{\pi}\arccos\left[\exp\left(\frac{-B(r-r_{hub})}{2r\sin\phi}\right)\right]$$

In the refined tip loss correction of De Vries, both the induced velocities and the mass flux are corrected. Once again, Eq. (15) is corrected and becomes.

$$C_T = \begin{cases} 4aF(1-a) & \text{if } a \le a_c \\ 4F(a_c^2 + a(1-2a_c)) & \text{if } a > a_c \end{cases} \tag{17}$$

And axial induction factor, a, is:

$$a = 1 + 0.5(K(1-2a_c)) - 0.5\sqrt{[K(1-2a_c)+2]^2 + 4(Ka_c^2 - 1)} \quad (18)$$

Where $K = \dfrac{4F\sin^2\phi}{\sigma C_n}$

And a_c is approximately 0.2

The chord distribution as defined by Eq. (19)

$$c(r) = \frac{2\pi V_0 BEP}{BC_l\Omega} \quad (19)$$

3. Proposed solution of axial induction factor

The angular induction factor obtained by resolution equation below.

$$b^2 + b\left(1+\frac{m}{\lambda_r}\right) + \frac{1}{\lambda_r^2}\left(a(1-m\lambda_r) - a^2\right) = 0 \quad (20)$$

Where m= C_l/C_d is the glide ratio

The second order equation, admit two solutions, the positive solution is expressed below:

$$b = -\left(1+\frac{m}{\lambda_r}\right) + \sqrt{\left(1+\frac{m}{\lambda_r}\right)^2 - \frac{4}{\lambda_r^2}\left(a(1-m\lambda_r) - a^2\right)} \quad (21)$$

The formulation of axial induction factor as follow:

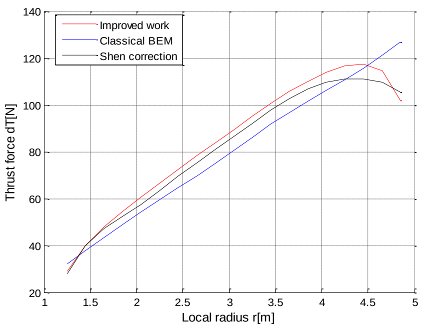
$$\frac{b}{1-a}\frac{\dfrac{S}{e^{1-a}}}{\sqrt{1-\left(\dfrac{S}{e^{1-a}}\right)^2}} - \frac{2}{\lambda_r^2}(1-a)(1-2a-m\lambda_r)\frac{1}{\sqrt{\left(1+\dfrac{m}{\lambda_r}\right)^2 + \dfrac{4}{\lambda_r^2}\left(a^2 + a(m\lambda_r - 1)\right)}} + \left(1+\frac{m}{\lambda_r} - \sqrt{\left(1+\frac{m}{\lambda_r}\right)^2 + \frac{4}{\lambda_r^2}\left(a^2 + a(m\lambda_r-1)\right)}\right)\cos^{-1}\left(\frac{S}{e^{1-a}}\right) = 0 \quad (22)$$

The power output is defined by:

$$dP = \Omega * dM \quad (23)$$

4. Analysis results and discussions

For the UAE Phase IV turbine, there are 2 blades, with twist and chord distributions variables along the blade and a radius of 5.03 m. The airfoil is the S809, constant throughout the rotor and the rotation is kept constant at 72 rpm. The mathematical model solution is obtained using the MATLAB numerical approach, and quickly convergence is reached after a reasonable number of iterations.



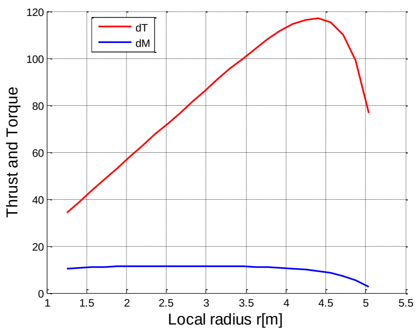


Fig. 1. Thrust force distribution along the blade

Fig. 2. Thrust and torque distribution along the blade

Figure 1 shows that the proposed model gives better results for the thrust force compared to those in classical BEM and Shen's corrections. In the blade tip region, the obtained thrust force profile changes direction and decreases rapidly, it is generally in agreement with that of Shen and disagreement with that of classical BEM.

The thrust and torque distribution are presented in figure 2. The thrust varied linearly, but at the hub and tip blade are curved by tip-hub loss factor effects. Especially in the tip region, the large over-prediction of loads is greatly reduced to avoid blade breaking and to reduce the Swirl phenomenon. For the torque, the results are constant along the blade up to a radius 4.5 m, and then the torque decreases slowly due to the tip loss factor.

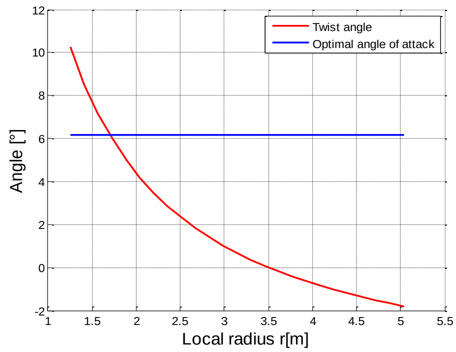


Fig.3. Optimum distributions of twist and attack angles

Figure 3 shows the optimum distributions of twist and attack angles versus of the local blade radius. The twist angle decreases exponentially from 10.25° to -1.8° near the blade tip. The torsion of blade is important and close to 12.5 °, which provides more power performances; on the other hand, the turbulence phenomenon decreased due to by increasing the difference between the twist angle of hub and tip of blade.

5. Conclusion

The optimum aerodynamic blade geometry was determined using iterative process for considering a new formulation of axial induction and tip loss factors. The obtained results are compared with literature and are in good accuracy. The following remarks are addressed:

- The improved BEM method is made by introducing new correlations of axial and tangential factors.
- In future study, we will propose a new approach to correct the lift and drag coefficients in post-stall region.

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