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Rotor Blade Performance Analysis with Blade Element Momentum Theory

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Abstract

In order to optimally explore and utilize wind energy, an optimal design of wind turbine propeller blades needs to be obtained. Therefore, a computational method to analyze and optimize the performance of the blades needs to be developed. For that purpose, a computational method based on the Blade Element Momentum (BEM) theory is developed in the present study. In this method, the propeller blade is divided into several elements and it is assumed that there is no aerodynamic interaction amongst the elements. Furthermore, the equations from momentum and blade element theories are combined to obtain equations which are useful in blades design process. In the analysis, tip and root losses proposed by Prandtl are also implemented. The computation results are validated using Qblade software. A good agreement can be found from comparison of the results computed from the developed BEM and QBlade.

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Keywords: Blade element momentum; momentum theory; NACA2415 airfoil; QBlade; rotor design; wind turbine.

Nomenclature

a	axial induction factor	P	turbine power
a'	angular induction factor	T	thrust force
C_L	lift coefficient	V	wind speed
C_D	drag coefficients	ω	rotational speed
F	axial force	Ω	angular speed

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1. Introduction

Considering the importance of exploration and exploitation of renewable energy resources including wind energy in recent decade, a wind turbine with optimal blades performance needs to be developed. Therefore, for designing the wind turbine blades with optimal performance, various methods have been established and implemented by researchers and scientists to analyze and optimize the performance of the wind turbine blades. Choosing the appropriate method to be adopted in blades designing process depends on the level of required results accuracy.

In the present study, a computational method based on the Blade Element Momentum (BEM) theory is developed. The BEM method is known to able to provide a closed form solution with relatively simple procedures. The method was originally developed from momentum theory and blade element theory [1]. By combining both methods, useful relations to be used in propeller blades design can be obtained. From this original method, various modifications have been performed and corrections are included by several researchers such as Prandtl tip and root losses [1], 3D correction [2], Reynold number drag correction [3], etc.

When using the BEM method, the propeller blade is divided into several elements. It is assumed that each element is independent and the fluid flow over elements has no interaction. Moreover, the forces and moments are computed in each element so that total forces and moments are obtained by integrating the individual forces and moments on each element.

In order to demonstrate the computation procedures and validate the results of the BEM method developed in the present study, a propeller blade with NACA2415 airfoil shape, is chosen. Only tip and root losses proposed by Prandtl [1] which are implemented in the present study. The computation results from the developed BEM is validated using a software package called QBlade [4]. It is a free software based on GNU license which provides friendly interface for propeller design analysis and optimization processes based on the BEM method. It is found from the study that the results computed from the developed BEM method has a good agreement with the ones from QBlade software.

2. Solution Method

In the present study, the Blade Element Momentum (BEM) theory is adopted as the main computation method. The method is combination of momentum theory and blade element theory. The blade element theory sometimes is also called strip theory.

2.1. Momentum Theory

From momentum theory, when assuming that the blades could produce power without rotation, the axial force (F) can be obtained using the following equation [5]

$$dF = 4a\left(1-a\right)\rho_a V^2 \pi r dr \tag{1}$$

Where ρ_a is air density, V the wind velocity far downstream, r the distance of the element from hub and a the axial induction factor which could be written as

$$a = \frac{V - V_T}{V} \tag{2}$$

Where V_T is the wind velocity far upstream. When rotation is introduced in the model, the thrust (T) can be obtained using the following relation [5]

$$dT = 4a'(1-a)\rho_a V\Omega\pi r^3 dr \tag{3}$$

Where *a'* is the angular induction factor which can be written as

$$a' = \frac{\omega}{2\Omega} \tag{4}$$

Where ω is blade rotation speed, and Ω the angular speed.

2.2. Blade Element Theory

In the blade element theory, the elements are considered to have infinitesimal thickness. These strips are aerodynamically independent and do not have interference between them. With those assumptions, the axial and thrust forces can be written as [5]

$$dF = \frac{1}{2}\rho_a BCW^2 dr\left[C_L \cos\phi + C_D \sin\phi\right] \tag{5}$$

$$dT = \frac{1}{2}\rho_a BCW^2 r dr\left[C_L \sin\phi - C_D \cos\phi\right] \tag{6}$$

Where B is number of blades, ϕ the inflow angle, W the resultant velocity, C the airfoil chord, and C_L and C_D the lift and drag coefficients, respectively.

2.3. Blade Element Momentum (BEM) Theory

The main principle of the BEM method is to combine the equations from momentum theory and blade element theory to obtain useful relations. Equating Eq. (1) with Eq. (5) and Eq. (3) with Eq. (6), the following relations can be obtained.

$$\left.\begin{aligned} 8a(1-a)V^2\pi r &= BCW^2\left[C_L \cos\phi + C_D \sin\phi\right] \\ 8a'(1-a)V\Omega\pi r^2 &= BCW^2\left[C_L \sin\phi - C_D \cos\phi\right] \end{aligned}\right\} \tag{7}$$

Substituting W into Eq. (7) and rearranging them, the following relations can be written [6]

$$\frac{a}{(1-a)} = \frac{\sigma_r}{4}\frac{\left[C_L \cos\phi + C_D \sin\phi\right]}{\sin^2\phi} \tag{8}$$

$$\frac{a'}{(1+a')} = \frac{\sigma_r}{4}\frac{\left[C_L \sin\phi - C_D \cos\phi\right]}{\sin\phi\cos\phi} \tag{9}$$

Where σ_r is known as local solidity ratio which can be written as

$$\sigma_r = \frac{BC}{2\pi r} \tag{10}$$

Tip and Root Losses

Losses will be experienced by the blade at the tip and root. The losses need to be also considered. An approximate method of estimating the tip losses effect has been given by L. Prandtl as follows [1]

$$F = \frac{2}{\pi}\cos^{-1}\left(\exp\left(-\frac{B}{2}\frac{R-r}{r\sin\phi}\right)\right) \tag{11}$$

where R is the maximum rotor radius. By including the tip and root losses effect, the relations shown in Eqs. (8) and (9) are modified to be

$$\frac{a}{(1-a)} = \frac{\sigma_r}{4F}\frac{\left[C_L\cos\phi + C_D\sin\phi\right]}{\sin^2\phi} \tag{12}$$

$$\frac{a'}{(1+a')} = \frac{\sigma_r}{4F}\frac{\left[C_L\sin\phi - C_D\cos\phi\right]}{\sin\phi\cos\phi} \tag{13}$$

As can be seen in Eqs. (12) and (13), there are several unknown variables which need to be determined which are a, a', and ϕ. In order to determine these variables, equations above need to be solved simultaneously using a standard iteration method. After the axial and angular induction factors can be determined, they are used to compute the turbine thrust forces and power.

3. Rotor Design Procedure

In order to design a propeller rotor using the blade element momentum (BEM) method described in the previous subsection, several variable needs to be determined in the beginning. These variables are number of blades, blade radius, pitch and twist angles, rotor rotation, and wind speed. Using the input data, the following procedure is performed

- Guess the axial and angular induction factors (a and a')
- Determine the wind inflow angle (ϕ)
- Determine the angle of attack (α)
- Determine the value of C_L and C_D from extrapolated airfoil experimental data
- Re-compute a and a'
- Compare the new a and a' with the ones obtained from previous iteration
- Continue iteration until converged

The value of a and a' obtained after the computations are converged, are used to compute the total axial force (thrust) and power of the turbine.

4. Computation Model

The present study uses airfoil shape of 2415 for demonstrating the computation procedures and results of the developed BEM. The same airfoil has been used by Mahmuddin [7] to study the effect of flat plate theory assumption in extrapolating lift and coefficients using Viterna method. The shape of the airfoil is shown in the following figure.

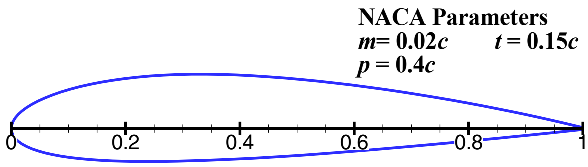
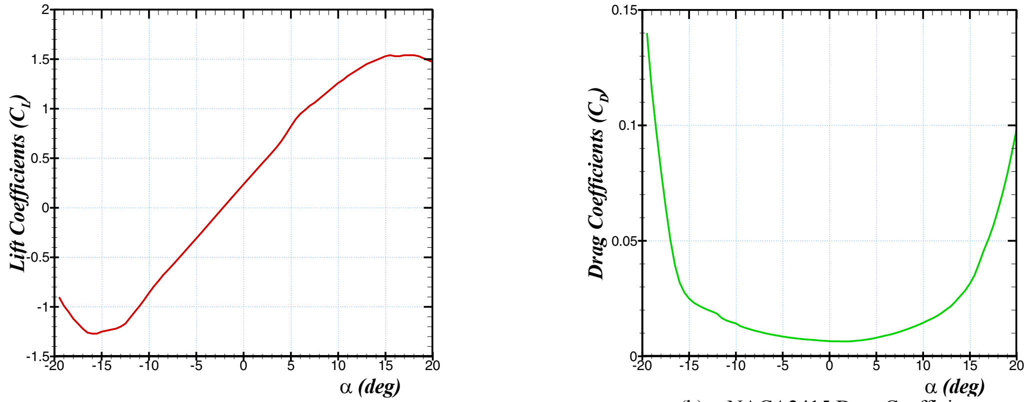


Figure 1. NACA2415 airfoil shape [7]

Using the airfoil shape shown in. Fig. 1, the lift and drag coefficients of the airfoil is computed from QBlade software. The computation results are shown in the following figure.



(a) NACA2415 Lift Coefficient (b) NACA2415 Drag Coefficient

Figure 2. NACA2415 Lift and drag coefficients

In order to obtain the full 360° lift and drag coefficients which are needed in the BEM computation, the C_L and C_D shown in Fig. 2 are extrapolated using Viterna method. More detail information about the method can be found in reference [7]. The other input data used in computation are shown in the following table

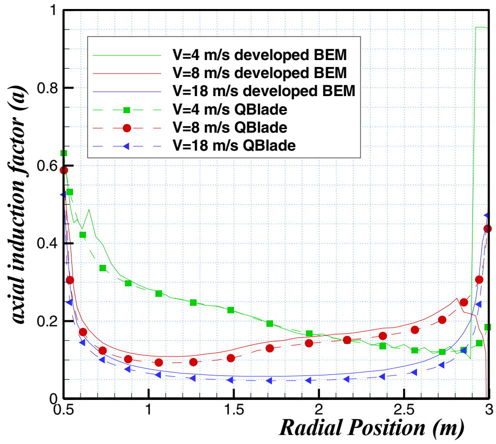
Table 1. Computation input data

Parameters	Unit	Parameters	Unit
Number of Blade (*B*)	3	Chord (*C*)	0.3 m
Radius (*R*)	5.03 m	Pitch angle (ϕ)	10 degree
Root Extension (hub)	0.5 m	Twist angle	0 degree
Rotational Speed (*N*)	71.3 rpm		

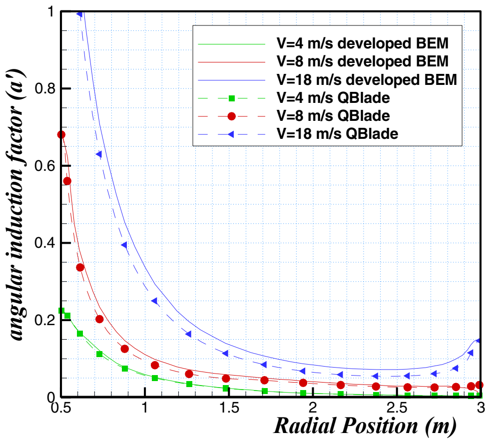
As shown in the Table 1, the computed blade has uniform chord length and no twisted angle (untapered and untwisted blades).

5. Computational Results and Discussion

A computer program based on the formulation and procedures described in the preceding section is developed. Using the input data shown in Table 1, the computation is performed. The computation results in terms of axial and angular induction factors are shown in the following figure



(a) Axial induction factor



(b) Angular induction factor

Figure 3. Axial and angular induction factors computed by the developed BEM and QBlade software

In Fig. 3 above, the axial and angular induction factors are shown for varying radial position. It can be observed from the figure that slight differences of the results computed by developed BEM and QBlade can be noticed especially for higher wind speed region. The differences are caused by the slight differences of lift and drag data extrapolation method implementation in the developed BEM and QBlade software.

The value of *a* and *a'* shown in Fig. 3 are used to compute the propeller blade power. The computation results are shown in Fig. 4 below.

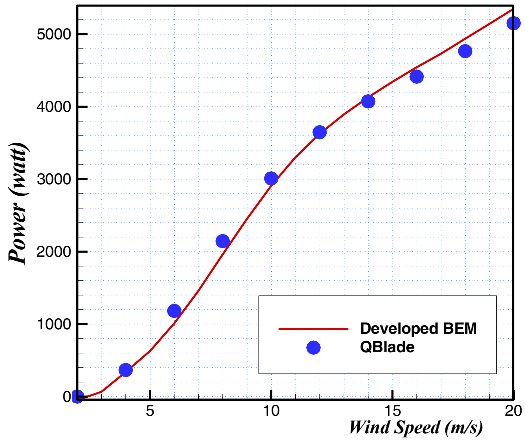


Figure 4. Comparison of propeller blade power with tip and root losses

It can be noted from the figure that there is also a slight discrepancy of results especially around high wind speed region. The discrepancy is the effect of slight differences of the *a* and *a'* obtained previously. However, it could be summarized from the figure that the overall tendency and magnitude of the results are shown to be in a good agreement.

6. Conclusion

The present study developed a computational method based on (BEM) theory. A propeller blade which uses NACA2415 airfoil shape was chosen to demonstrate the computation procedures and results. Tip and root losses proposed by Prandtl were also implemented. The developed BEM computation results are validated using the ones computed from QBlade software where they were found to be in a good agreement.

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References

[1] Glauert H. Airplane Propellers. In: Durand WF, editor. *Aerodynamic Theory*, Berlin: Julius Springer; 1935, p. 169–360.

[2] Snel H. *Sectional Prediction of 3-D Effects for Stalled Flow on Rotating Blades and Comparison with Measurements*. Petten: Netherlands Energy Research Foundation ECN; 1993.

[3] Hernandez A, Crespo J. Aerodynamic calculation of the performance of horizontal axis wind turbines and comparison with experimental results. *Wind Eng* 1987;11(4):177–187.

[4] Marten D, Wendler J. *QBlade Guidelines*. Berlin: Berlin Technical University; 2013.

[5] Moriarty PJ, Hansen AC. *AeroDyn Theory Manual*. Colorado: National Renewable Energy Laboratory; 2005.

[6] Ceyhan O. *Aerodynamic Design and Optimization of Horizontal Axis Wind Turbines by Using BEM Theory and Genetic Algorithm*. Ankara: Middle East Technical University; 2008.

[7] Mahmuddin F. The Effect of Flat Plate Theory Assumption in Post-Stall Lift and Drag Coefficients Extrapolation with Viterna Method. *J. Subsea Offshore* 2016;6:9–13.

Biography

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