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Aerodynamic Analysis of HAWT using Blade Element Method and Q-Blade Software

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ABSTRACT

Blades are the very important components of wind turbines in order to convert wind energy to mechanical or electrical energy. Therefore, the aerodynamic forces acting on the horizontal wind turbine blades have an important role in their performance. The objective of this paper is to investigate the aerodynamic characteristics and power generation properties for a NREL PHASE VI wind turbine blade. For this purpose, an analysis procedure based on the Blade Element Method (BEM) is demonstrated for a horizontal-axis wind turbine model (HAWT), and the methodology approach is discussed in detail throughout this paper. In this study, a Math Lab code has been developed for analyzing a model of Horizontal-Axis Wind Turbine (HAWT) in order to display aerodynamic behaviour on the blade. The NACA S809 airfoil was selected for the analysis of the wind turbine blade, where the tip and root losses proposed by Prandtl are also executed. The calculated results are validated using Q-Blade commercial software at rated wind speed of 10 m/s and show that the BEM is a good method of aerodynamic investigation of a HAWT blade

التحليل الديناميكي الهوائي ل HAWT باستخدام طريقة عنصر الشفرة وبرنامج Q-Blade

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الكلمات المفتاحية:
قسم شفرة توربينات الرياح
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شفرة Q
توربينات الرياح NREL VI

الملخص

تعتبر الريش الدوارة من المكونات المهمة جدًا لتوربينات الرياح من أجل تحويل طاقة الرياح إلى طاقة ميكانيكية أو كهربائية. ولذلك فإن القوى الديناميكية الهوائية المؤثرة على ريش توربينات الرياح الأفقية لها دور مهم في أدائها. لذا فأن الهدف من هذا البحث هو دراسة الخصائص الديناميكية الهوائية وخصائص توليد الطاقة لريشة توربينات الرياح NREL PHASE VI. ولهذا الغرض، تم توضيح إجراء تحليل يعتمد على طريقة عنصر الريشة (BEM) لنموذج توربينات الرياح ذات المحور الأفقي (HAWT)، وتتم مناقشة نهج المنهجية بالتفصيل في هذه الورقة. في هذه الدراسة، تم تطوير كود معمل الرياضيات لتحليل نموذج لتوربينة الرياح ذات المحور الأفقي (HAWT) من أجل عرض السلوك الديناميكي الهوائي على الشفرة. تم اختيار الجنيح NACA S809 لتحليل ريشة توربينات الرياح، حيث يتم أيضًا تنفيذ خسائر الطرف والجذر التي اقترحها Prandtl. تم التحقق من صحة النتائج المحسوبة باستخدام برنامج Q-Blade التجاري عند سرعة رياح مقدرة تبلغ 10 م/ث، وتُظهر أن BEM طريقة جيدة للتحقيق الديناميكي الهوائي لريشة HAWT.

1. Introduction

Energy is essential to human civilization development. With progress of economics and socialization, there is an expanding demand on renewable energy resources to secure energy supply, such as solar power, wind power, tide and wave power etc. As a clean renewable resource, wind power plays a more and more important role in modern life. Considering the significance of the investigation and exploitation of wind energy resources, including a wind turbine ideal blade design needs to be developed. The energy efficiency of wind energy system

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generation has an important impact in terms of economic analysis of this type of renewable energy. The efficiency in these systems depends on many subsystems: blades, electric generator, gearbox and control. Certain factors involved in the effectiveness of the blades are the characteristics of the wind. Wind turbine design and analysis require efficient and methods of calculating in terms of aerodynamics and structure performances. In order to design a wind blade with perfect efficiency, some different methods have been applied by engineers and researchers to analyze and optimize the performance of the wind turbine blades. The choice of the appropriate method for the blade design process depends upon the level of accuracy of the required results. In this study, a computerized code based on the Blade Element Method (BEM) is written and developed. It is well-known that BEM can provide a relatively simple closed-form solution. Glauert H. has developed blade element theory from momentum theory [1]. By combining the two methods to achieve useful relationships and to be used in the design of the propeller blades. Because its simplicity, the blade element method is used widely in the energy power industry, which has provided precise performance as reported in many previous researches [2]. The aerodynamic forces acting on a local airfoil study by the blade element method. According to the aeronautics theory, the forces that act on the wing are Lift and Drag which are perpendicular to the wind direction and in the same direction respectively. The geometry of a blade profile can have a direct effect on the coefficients of Lift, Drag and pitch moment during operation and consequently on the quantity of energy that can be generated by a wind turbine [3]. Structural, aerodynamic and control concerns are involved in the design of optimal blades. However, the design cycle can be practically approached as an iterative and stepped method. For aerodynamic optimization the blade can be modelled as a series of sections along the pitch axis. Each section has an airfoil shape, chord length and attach angle which is the result of a collective pitch angle and a local twist one. 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. It is assumed that each element is assumed to be independent and there is no interaction between the fluid-flow over the elements. Designers of wind turbines use shape optimization to maximize blade perform and performance when using wind energy. Airfoil shape optimization increases aerodynamic performance in this case by reducing drag or/and increasing the L/D ratio of lift to drag. In order to investigate and validate the results of the blade element method, a propeller blade with an airfoil shape using Genetic Search Algorithms GAs is adopted. In this paper, airfoil shape optimization using Genetic Search Algorithms GAs is adopted. A penalty function is utilized that directs the optimization process toward the solution. Only tip and root losses suggested by Prandt [3] have been introduced in the present analysis. An aerodynamic code, based on invisid-viscous interaction method is called to calculate the lift, drag and pitching moment coefficients for a given angle of attack and Reynolds number. The aerodynamic coefficients of each candidate airfoil are assessed by the objective function which is based on the weighted sum method and a penalty function is implemented to enforce constraints if they are violated. This optimization methodology can be applied to direct and inverse design problems. Aerodynamic shape design/optimization is a challenging problem because the governing fluid dynamics are nonlinear [4]. A genetic algorithm is a good shape optimization algorithm because it can deal with large number of continuous and integer design variables as it searches highly multi modal and discontinuous design spaces [4]. National Renewable Energy Laboratory (NREL) has developed a family of airfoils for HAWT applications [4] since 1984. The main objective of the present paper is to minimize drag of NREL S809 laminar flow airfoil at three angles of attack in the middle of the operating range at Reynolds number of 5.5x105. This airfoil is 21% thick whose design and experimental data are published in [4]. NREL Phase II, Phase III, and Phase VI HAWT blades are composed of S809 airfoil from root to tip. The flow is in compressible where laminar separation can occur on the airfoil suction side for angles of attack ranging from 0 to 5.13 degrees. Turbulent trailing edge separation can also occur at high angles of attack

2. Blade Element Method

The blade-element method is an additional method using in analyzing and tracking the behaviour of blades due to their motion through the air. In horizontal axis wind turbine (HAWT), the rotor is made of a number of sections (elements) as shown in Fig. 1. An airfoil located at distance r from the center of rotation will feel a relative velocity V_{rel} inclined at an angle ϕ with the rotation plane as illustrated in Fig. 2. The local angle of attack α obtained from the pitch angle of the airfoil θ, which is known for particular blade, the velocity (V_a) at the rotor plane and the rotational velocity (V_{rot}) at the rotor plane can be determined from velocity diagram in Fig. 2 and represented as:

$$\alpha = \phi - \theta \quad (1)$$

Where the flow angle is found as:

$$\phi = \tan^{-1}(\frac{V_a}{V_{rot}}) \quad (2)$$

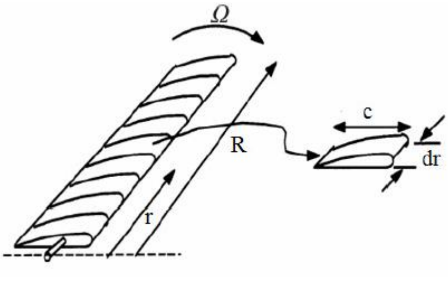


Fig.1: Schematic of blade elements

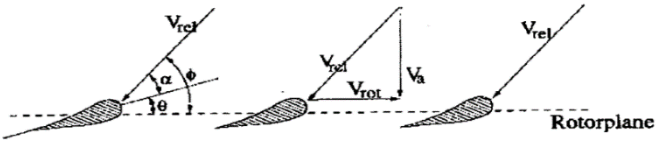


Fig. 2: Blade geometry for analysis of a HAWT

An induced velocity affect assumes as a function of radius. In the axial direction, the induced velocity is specified through the axial induction factor a as aV_0 where V_0 represents the undisturbed wind speed. In the rotor wake, the induced tangential velocity is specified through the tangential induction factor a' as $2a'\omega r$, where ω represents the angular velocity of the rotor and r is the radial distance from the rotational axis. The tangential induced velocity in the rotor plane is approximately$a'\omega r$, since the flow does not rotate upstream of the rotor. The velocities V_a and V_{rot} are calculated by the following equations:

$$V_a = (1 - a)V_0 \quad (3)$$

$$V_{rot} = (1 + a')\omega r \quad (4)$$

Also, if the Lift and Drag coefficients $C_l(\alpha)$ and $C_d(\alpha)$ are known as well for the airfoil section applied along the blade, the force distribution in normal $C_n(\alpha)$ and tangential $C_t(\alpha)$ directions are easily computed from the lift and drag coefficients, as.

$$C_n = C_1 \cos\phi + C_d \sin\phi \quad (5)$$

$$C_t = C_1 \sin\phi - C_d \cos\phi \quad (6)$$

Using integration along the span, the global loads such as the power output and the root bending moments of the blades can be calculated by integrating over the blade length.

$$P = 4\pi\rho\omega^2 V_0 \int_0^R a'(1 - a')r^3 dr \quad (7)$$

$$M = \int_0^R \frac{\frac{1}{2}\rho B V_0 (1-a)\omega r(1+a')}{\sin\phi\cos\phi} c C_t r\, dr \quad (8)$$

a. Prandtl's Tip-Loss Factor

The vortex system in the wake is different for a rotor with a finite number of blades from a rotor with an infinite number of blades. L. Prandtl derived a correction factor F to be applied in the equations for axial and radial induction factors a and a'

$$dT = 4\pi\rho V_0^2 a(1 - a)F dr \quad (9)$$

$$dM = 4\pi r^3 \rho V_0 \omega(1 - a)a' F dr \quad (10)$$

F is calculated as:

$$F = \frac{2}{\pi}\cos^{-1}(e^{-f}) \quad (11)$$

Where:

$$P = 4\pi\rho\omega^2 V_0 \int_0^R a'(1 - a')r^3 dr \quad (12)$$

$$f = \frac{B}{2}R - \frac{r}{2r\sin\phi} \quad (13)$$

Where B is the number of blades, R is the overall radius of the rotor, r is the local radius and ϕ is the flow angle. The equations for a and a' are respectively:

$$a = \frac{1}{\left[\left(\frac{4F\sin^2\phi}{\sigma C_n}\right)+1\right]} \quad (14)$$

$$a' = \frac{1}{\left[\left(\frac{4F\sin\phi\cos\phi}{\sigma C_t}\right)-1\right]} \quad (15)$$

If the axial induction factor is larger than approximately 0.4, the simple momentum theory breaks down, as shown in Fig. 3. Different empirical evaluations of the thrust coefficient CT can be made to fit with measurements;

$$C_T = \begin{cases} 4a(1-a)F, & a \le a_c \\ 4\left(a_c^2 + (1 - 2a_c)\right)F, & a > a_c \end{cases} \quad (16)$$

The corresponding value of the induction factor a is given by the equation

$$a = \frac{1}{2}\left[2 + K(1 - 2a_c) - \sqrt{(K(1 - 2a_c) + 2)^2 + 4(Ka_c^2 - 1)}\right] \quad (17)$$

Where:

$$K = \frac{4F\sin^2\phi}{\sigma C_n} \quad (18)$$

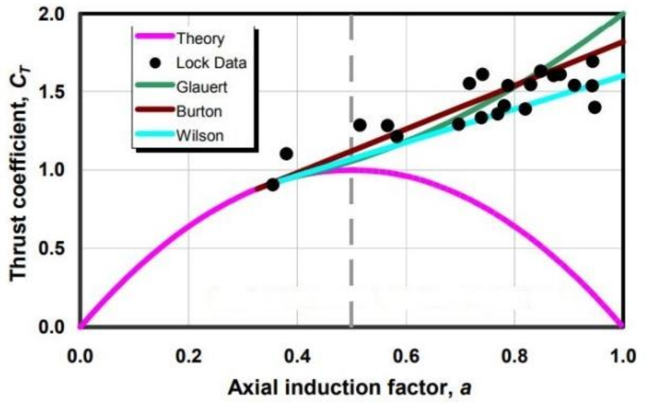
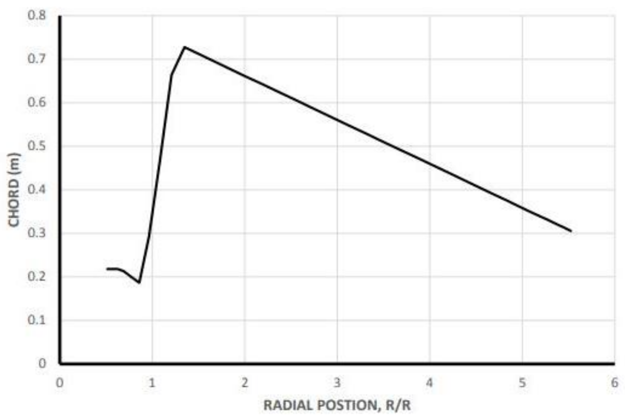


Fig. 3: Different expressions for the thrust coefficient CT vs. axial induction factor a

b. Blade Configuration

The NREL/NASA Phase VI wind turbine features two blades, with fixed-yaw and fixed-pitch (stall-regulated) regulation. The entire blade span was used by a single airfoil S809. It can be seen in figure 4 that the blade had a nonlinear twist and almost linear taper [5] thesis. In the NASA-Ames wind tunnel, power measurements were performed at wind speeds that ranged from 7m/s to 25 m/s. The tip pitch angle of the blades was fixed to 3 towards during the test and the yaw angle was locked at 0° [6].



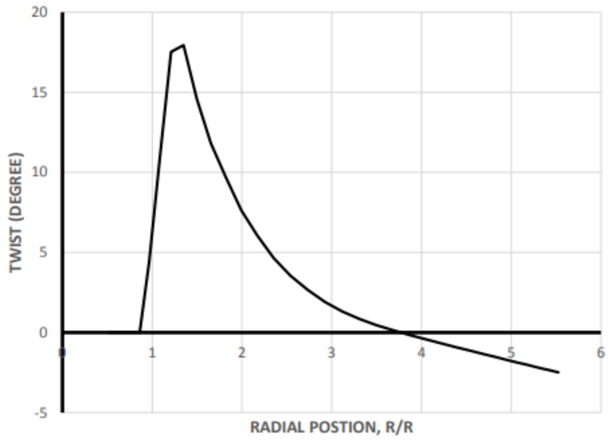
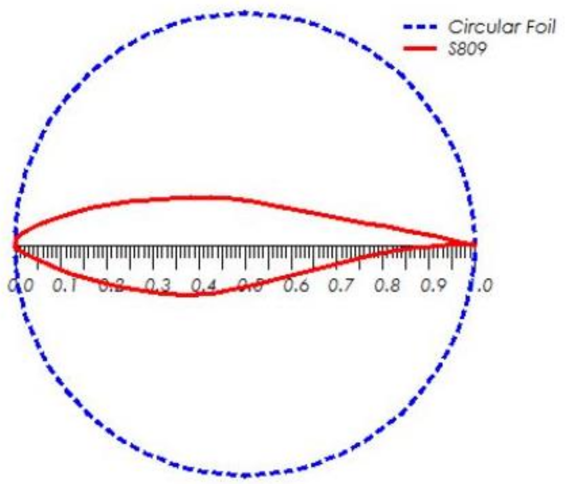


Fig 4: Chord and twist angle distributions of the NREL/NASA Phase VI wind turbine blade

c. Blade Airfoil (S809) Characteristics

Aerodynamic coefficients for S809 have been provided by NREL and also computed by a number of universities, for instant University of Technology at Reynolds number of 1 × 106 [7, 8]. In addition to that, Ohio State University (OSU) conducted other measurements at Reynolds number of 1 million and from Colorado State University at Reynolds numbers from 0.3×106 to 0.65×106 were compared with the TUDelft results by C. Lindenburg [9]. For this study, the airfoil will have a rotational speed of 100 RPM at a wind speed ranging from 1-20 m/s and an angle of attack ranging from -10° to 30° while the density and viscosity of the air have been both taken at sea level conditions with a relaxation factor of 0.3. The shape and aerodynamics date of airfoil are shown in the following figure.



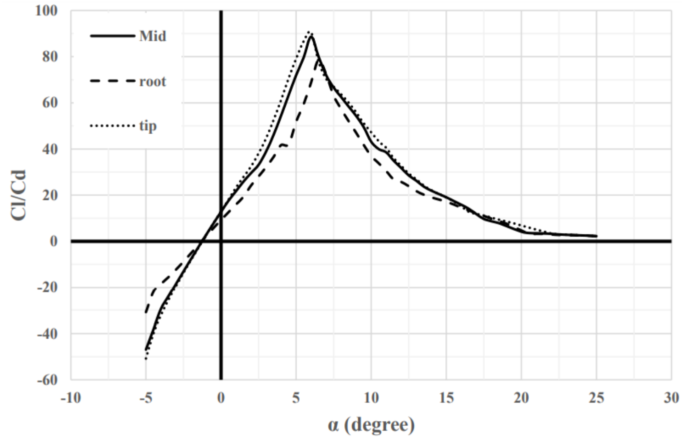
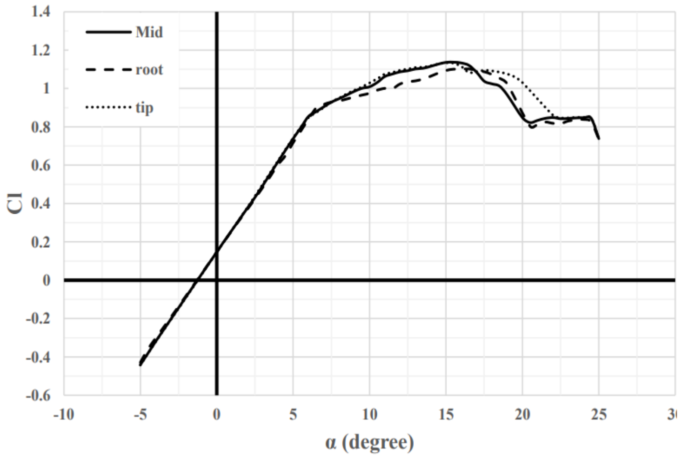
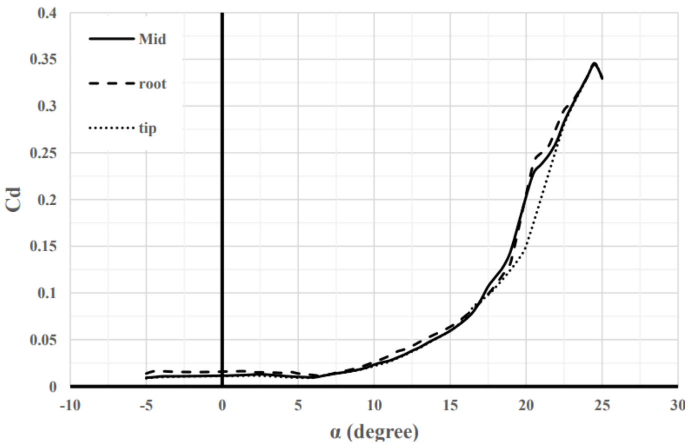


Fig. 5: Air foil S809 shape and aerodynamic data

Using the airfoil shape shown in Fig. 5, the lift and drag coefficients of the airfoil are computed with blade thrust and power coefficients by using Q-Blade software [10]. The computation results are shown in the following figures. Airfoil shape affects how pressure varies along the blade. Well-designed airfoils optimize pressure distribution, enhancing performance at various wind speeds [11}. Therefore, effective management of pressure distribution on wind turbine blades is essential for maximizing energy capture, ensuring structural integrity, and optimizing overall performance.



(a) S809 Lift coefficient vs. angle of attack



(b) S809 Drag coefficient vs. angle of attack

Fig. 6: S809 Lift and Drag coefficients variations at root, mid, and tip sections of the blade.

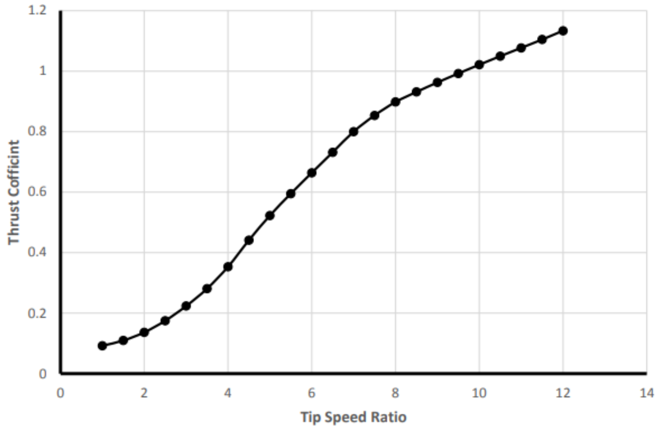


Fig. 7: Thrust curve predicted with Tip speed ratio using Q-Blade

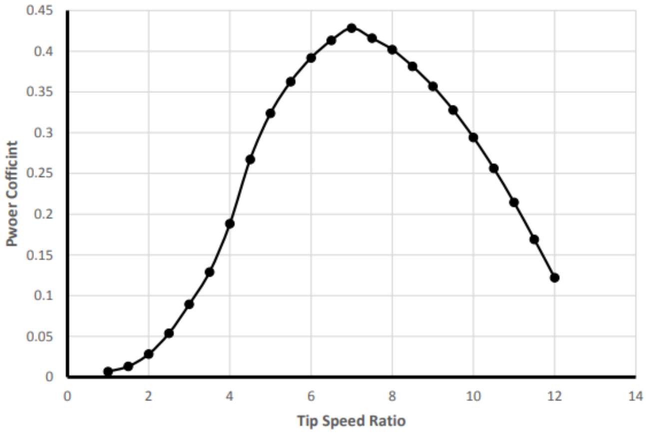
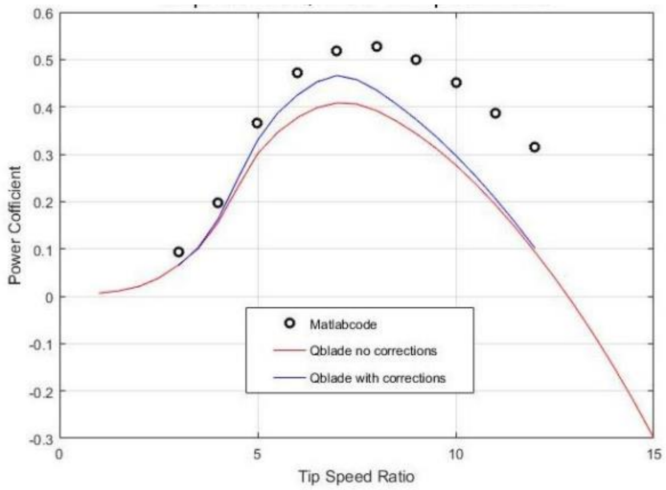


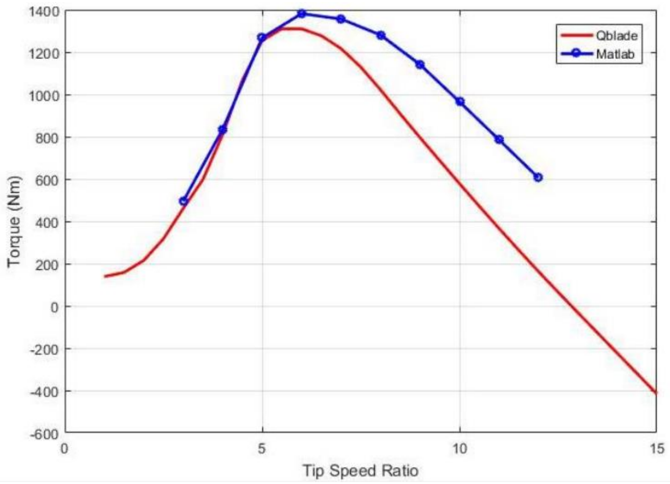
Fig. 8: Power curve predicted with Tip speed ratio using Q-Blade

3. Computational Results and Discussion

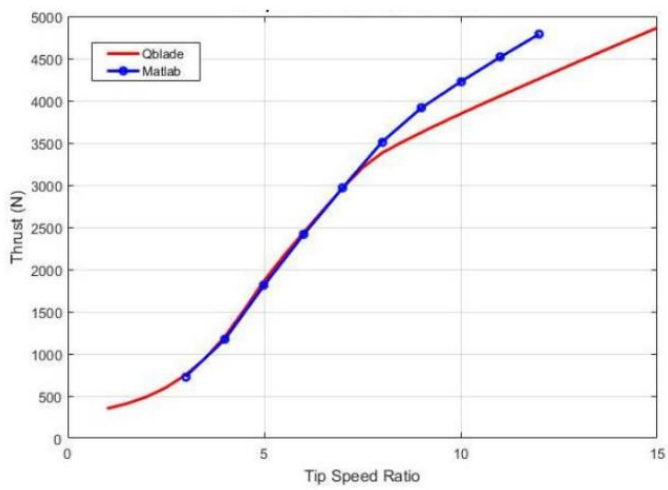
Consequently, the BEM and Q-blade software are very successful in HAWT blade investigations. The Tip-lose factor and models were also combined into the Q-Blade to predict the blade performance and there is a good comparison of torque and thrust in each section between the Q-blade and Mathlab code. To validate the results gained by Matlab routine in order to ensure the accuracy of the gained results, a comparison between the results gained by the Matlab routine and the Q-Blade results was conducted. A Comparison of the power coefficient, torque and thrust at a tip speed ratio (TSR) ranging from 3 to 12 are shown in Fig. 10. Results show that the MATLAB routine generated curves that are generally close to the Q-Blade results. Results of Matlab routine follow the same trend of the Q-Blade software despite the power, thrust and torque being over estimated after the maximum power. The analysis results show that the maximum difference in power is at the values of 0.5 and 8 (TSR) and in thrust is at the value of 4750 (N) and 12 (TSR) and in torque is approximately at 1400 (Nm) and 6 (TSR) these discrepancies are an interesting point of research for further study. Therefore, figure 10 presents an overall picture of the obtained results along with the Mathlab and Q-Blade. The results produced by two solutions are close to each other till 5 of tip speed ratio for power and torque coefficients respectively. However, the thrust coefficient results were matching with a good agreement till 5.5 of tip speed ratio and after that are started in divergence. As shown in Figure 3 relative velocity prediction at all radial positions, Q-Blade results demonstrate good agreements with NREL (cal) measurement.



(a) Power vs. TSR



(b) Torque vs. TSR



(c) Thrust vs. TSR

Fig 9: Analysis comparison of wind turbine blade power, torque and thrust with tip speed ratio

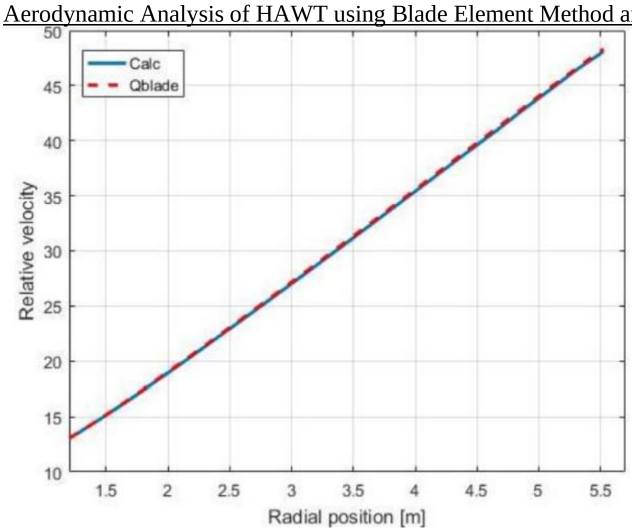


Fig. 10: relative velocity predicted with Q-Blade and NREL measurements (cal)

4. Conclusion

In this paper the blade element method calculation procedure was demonstrated, using NREL PHASE VI wind turbine. The airfoil aerodynamic coefficients and the geometric characteristics of the blade are imported from the Q-blade software which confines the comparison to the calculation procedure only. In this paper, the calculation procedure is presented and discussed. The primary aim of this paper was to compare a published BEM with Q-Blade software using a benchmark wind turbine. The obtained results show that the BEM method, which is one of the simple stands fastest methods used in wind turbine analysis, is able to make a good estimation of the total power thrust and torque of a HAWT wind turbine operating at, or close to, the desired conditions. Moreover, good agreement results with Q-Blade for TSR less than about 7 and tend to over-estimate power, torque and thrust for higher values of TSR. This trend suggests more investigation to the tip loss factors. As a general result, the BEM is a suitable method to study and simulate the effects of multiple design parameters on the performance of wind turbine rotors.

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