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Aerodynamic assessment of airfoils for use in small wind turbines

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Abstract. A successful blade design must satisfy some criterions which might be in conflict with maximizing annual energy yield for a specified wind speed distribution. These criterions include maximizing power output, more resistance to fatigue loads, reduction of tip deflection, avoid resonance and minimize weight and cost. These criterions can be satisfied by modifying the geometrical parameters of the blade. This study is dedicated to the aerodynamic assessment of a 20 kW horizontal axis wind turbine operating with two possible airfoils; that is Göttingen 413 and NACA 2415 airfoils (the Gottingen airfoil never been used in wind turbines). For this study parameters such as chord (constant, tapered and elliptic), twist angle (constant and linear) are varied and applied to the two airfoils independently in order to determine the most adequate blade configuration that produce the highest annual energy output. A home built numerical code based on the Blade Element Momentum (BEM) method with both Prandtl tip loss correction and Glauert correction, X-Foil and Weibull distribution is developed in Matlab and validated against available numerical and experimental data. The results of the assessment showed that the NACA 2415 airfoil section with elliptic chord and constant twist angle distributions produced the highest annual energy production.

Keywords: small wind turbine; blade element momentum; chord distribution; twist angle distribution; horizontal axis wind turbine; annual energy production

1. Introduction

Wind energy is a renewable abundant energy source which if adequately tapped can reduce the dependence on fossil fuels. Approximately 10 million MW of wind energy can be continuously harnessed. Large horizontal axis wind turbines are usually installed for electricity generation in sites with optimum wind conditions either on-shore or off-shore. These high capacity wind generators are normally connected to the electricity distribution grids, they are of dominated technology and many of them are installed in wind energy farms in operation around the world. Small wind turbines on the other hand are less efficient and not much popular because of their initial and maintenance costs and poor aerodynamic performance. Usually they are installed in small communities, in isolated and rural areas to produce electricity irrespective of favorable wind

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conditions.

Technical reviews available in the literature treat windmills technology, development, applications, and fundamentals as in Schubel and Crossley (2012) who prepared a detailed review of the current state-of-art for wind turbine blade design, including theoretical maximum efficiency, blade design, and blade loads. Karthikeyana *et al.* (2015) reviewed various optimization processes of blade and aerofoil geometry to increase power coefficient of small wind mills working below Reynolds number of 500,000. In their review Chehouri *et al.* (2015) presented techniques and strategies applied to wind turbine performance optimization and focused on the minimization of the cost of energy to be more competitively and economically attractive. Tummala *et al.* (2016) who presented a review on small scale wind turbines, their performance, blade design, control and manufacturing. Bai and Wang (2016) reviewed computational as well as experimental methods used to measure the aerodynamic performance of blades for horizontal axis wind turbines.

Many studies were devoted to the optimization of small windmills, blade geometry, twist angle distributions and airfoils sections most adequate for operation at low Reynolds numbers. Ceyhan (2008) proposed to optimize turbine blades to achieve the maximum power production by altering the rotational speed, the blade radius and the number of blades using the BEM method. Wang *et al.* (2012) provided an optimal blade design strategy for horizontal-axis wind turbines operating at different Reynolds numbers. The results demonstrated that the proposed blade optimization strategy can improve the aerodynamic performance. Liu *et al.* (2013) proposed a new method for a fixed-pitch fixed-speed wind turbine. The results demonstrated the good potential of the proposed method to achieve a low manufacturing cost and better power performance. Tang *et al.* (2015) reported the results of a direct method for the design and optimization of small wind turbine blades where Reynolds number, tip and hub, and drag effects were accounted for in the method. Karthikeyan and Suthakar (2016) conducted a numerical study to optimize the selection of suitable airfoils for small wind turbine applications at low Reynolds number. The designed airfoil showed better aerodynamic performance and high power coefficient. Vaz and Wood (2016) presented a new approach to the aerodynamic optimization of a wind turbine with a diffuser and compared the predictions with experimental results and reported good agreement. Purusothaman *et al.* (2016) proposed to evaluate the section of blades at the root, mid and tip regions using the Blade Element Momentum (BEM) method to determine the power curves by altering some parameters such as tip speed ratio, lift and drag coefficients and chord and twist angle distributions. Tahani *et al.* (2017) proposed the linearization of the chord and twist distributions to maximize the power coefficient.

Small wind turbines usually operate in non optimal wind conditions and their aerodynamic performance depends heavily on the geometry including the hub and tip parts as well as the airfoil section and distributions of chord and twist angle. They should be able to work efficiently at low Reynolds numbers. Many numerical and experimental studies were devoted to these issues to improve the efficiency, performance and achieve reasonable manufacturing and maintenance costs. Sahin *et al.* (2001) published the results of a study on small-scale horizontal axis wind turbine showing its high potential for applications in remote areas. Vaz *et al.* (2011) developed a mathematical model which accounts for the wake effect and the comparisons of their results with available models showed good agreement. Singh *et al.* (2012) presented the results of low Reynolds number airfoil designed for use in small wind turbines to improve startup, performance at low wind speed and small Reynolds numbers of 38,000-205,000. Hassanzadeh et al (2016) presented the results of a study to optimize the distribution of chord and twist angle of small wind turbine blade in order to maximize its Annual Energy Production and reported an increase of 8.51%. Shen *et al.* (2016) presented the results of a study to optimize the geometry of wind turbine blades, that is, distribution of the chord and twist angle. While, Gupta *et al.* (2017) reported the results of a study to design a rotor blade for Reynolds number 100,000. It is found that the coefficient of power is about 35.7%.

A wide variety of numerical models were used to simulate the aerodynamic performance of windmills while other experimental studies were dedicated to produce data for real performance and comparison with simulation results. Among the techniques utilized (the lifting line and lifting surface methods and many others) the BEM method is the most preferred because of its simplicity of implementation. Lanzafame and Messina (2007) developed a mathematical model for wind turbine design based on the blade element momentum theory and compared the numerical predictions with experimental data. Sharifi and Nobari (2013) proposed a new innovative algorithm to predict a distribution of pitch angle along the blade for maximum power production. A code is developed based on the blade element momentum theory. Sudhamshu *et al.* (2016) presented the results of a study of the effect of pitch angle on the performance of a horizontal axis wind turbine and correlated the power produced to the stall characteristics of the airfoil and blade. Costa-Rocha *et al.* (2018) presented the results of a study of the effects of variable blade pitch on the aerodynamic performance of a small turbine and highlighted the enhanced behavior due to the use of a pitch angle controller.

To account for the difference between an actuator disc with infinite number of blades and an actual wind turbine with a finite number of blades, Prandtl introduced the concept of tip loss to make BEM computations more realistic. Glauert (1935) corrected the induced velocity in the momentum equations and assumed that the tip loss only affects the induced velocity but not the mass flux. A refined tip loss model was later introduced by Wilson and Lissaman (1974) which was later improved by de Vries (1979) who refined further the tip correction. Furthermore, comparisons of BEM computations with experiments show that the Prandtl / Glauert tip loss correction method overestimates the loading close to the tip. Shen *et al.* (2016) presented the results of a study to improve the tip loss effect of rotors on the prediction of wind turbine performance. A new tip loss correction model is proposed and comparisons between numerical and experimental data showed better agreement of the loading in the tip region. Later, Maniaci and Schmitz (2016) reported the results of another study to improve the prediction of blade tip loads computed by blade-element momentum methods by using a higher order free-wake method. It was found that accounting for the effects of tip vortex rollup improved the tip correction loss.

The present numerical study is dedicated to investigate the effects of the airfoil section, twist angle and chord distributions on the aerodynamic performance and annual energy production of a 20kW horizontal axis wind turbine with the objective of determining the most adequate blade configuration for the highest energy output. A home built numerical code based on the Blade Element Momentum (BEM) method, X-Foil and Weibull distribution with both Prandtl tip loss and Glauert corrections is developed in Matlab and validated against available data. The effects of the chord and twist angle distributions on the aerodynamic performance of two rotors based on the Göttingen 413 and NACA 2415 airfoils are evaluated and discussed.

Motivation for this work stemmed up from the fact that small wind turbines, although they are attractive solutions for energy supply in isolated areas and small native communities as in the north of Brazil and Amazon lands, they are not receiving any reasonable attention for further development and efficiency improvements. Communities living in mountainous areas and places of difficult access as in Asia and Africa can also be attended by small wind turbines provided there are winds of reasonable velocity. High power wind turbines have highly sophisticated and well dominated technology. Small wind turbines on the other hand are less developed and not very popular because of their relatively poor performance. However, they are essential for these simple and isolated communities to help them preserving food, fish, meat and other essential items for their survival. These are some of the reasons why we devoted some research effort in this direction.

Contributions of the present study to the area of aerodynamics of small wind turbines include the detailed aerodynamic assessment of two airfoils, one of which never been used in wind turbines, with objective of making the rotor more versatile and cheaper. The Gottingen 413 and NACA 2415 airfoil are investigated as possible candidates for application in small horizontal axis wind turbines. Searching for a profile and blades that are easy to manufacture and at the same time have high power coefficients, the investigation included blades having constant and linear chord distributions and constant and linear twist angle distributions. The assessment was done by numerical trials, not using at the moment any optimization technique. Another contribution is a numerical code based on the Blade Element Momentum (BEM) method which uses X-Foil, Weibull distribution together with Prandtl tip loss and Glauert corrections in Matlab. This code is validated against available experimental and numerical data.

The present work is divided into the following sections, introduction section including literature review, a section on the formulation of the numerical code and the computational procedure, a section on the numerical treatment and validation of the computational code, a section on the results and discussion, a section for the conclusions and a final section of the references.

2. Formulation and computational procedure

2.1 Mathematical formulation

The model used in the present analysis is based on the Blade Element Momentum (BEM) method which couples the One Dimensional Momentum Theory with the Blade Element Theory. The basic formulation of the BEM method assumes no aerodynamic interference between the adjacent blades and that the force from the blades on the flow is constant in each annular element as shown in Fig. 1. This assumption is equivalent to considering the rotor having an infinite number of blades (Burton 2001). Although this assumption leads to considerable simplifications in the mathematical treatment it does not reflect the real situation where there is a finite number of blades of finite length provoking interacting induced velocity fields and aerodynamic interference between the adjacent blades.

As is known a finite blade will induce vortices at the free tip and nearly straight vortices at the root or the hub region. Due to the finite number of blades there is a tendency to form strong vortices emanating from the tip region. The induced velocity field adds more complications to the vortex system generated at the blade tip and travelling downstream in the wake of the blade. Prandtl introduced semi analytical factors to approximate the BEM method to the real situation, known as the axial induction factor (a) and the tangential induction factor (a'), as in Fig. 2. Therefore the tip loss correction can be viewed as a remedy to assuming finite number of blades and finite blade length.

The contribution of Prandtl was significant and strong drive for the continuous use of the BEM method for the prediction of aerodynamic performance of small and medium wind turbines. Later, Glauert (1963) suggested two additional corrections to Prandtl correction axial induction factor to be used when the value of $a > ac$, e $a < ac$, where $ac = 0.2$.

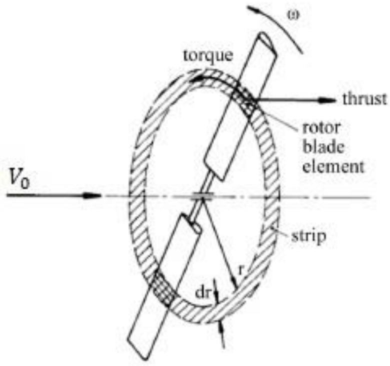


Fig. 1 Blade of rotor divided in annular elements (Hau 2006)

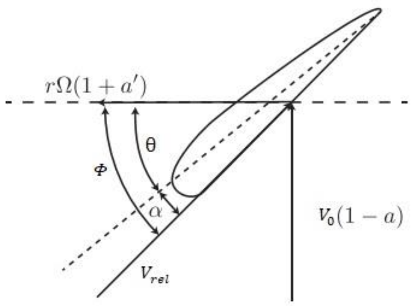


Fig. 2 Velocity triangle for the blade of rotor (Olczak *et al.* 2016)

The above general comments are provided to establish the basis of the model used in the present analysis. The BEM method and the Prandtl and Glauert corrections are used in a home-built code developed in Matlab, optimized and validated against available experimental and numerical results (Okita *et al.* 2018). Fig. 2 shows the calculation flow chart of the BEM method. Since the code is already treated in details and validated in (Okita *et al.* 2018), it is considered sufficient to highlight the main steps of the calculation procedure.

1. From the specified power requirement and the wind speed it is possible to estimate the wind turbine radius and consequently the blade length, subject to sonic limitation. The blade length is then divided into a number of radial segments or strips sufficient to represent adequately the blade. Tests were realized to verify the effect of the number of segments on the precision of the predicted results and it was found that a number of 40 segments produced variations less than 10-4 in the power coefficient which is considered satisfactory.

2. The airfoil section and its aerodynamic characteristics must be known to enable using the BEM method. In general, the choice of the airfoil section can be based on previous experience of use in similar wind turbine project. In the present study the airfoils Göttingen 413 and NACA 2415, not much used in windmills, are chosen for the present investigation. The objective is to evaluate their performance under the different variants of chord and twist angle distributions. Linear and tapered chord distributions as well as constant and linear twist distributions are variants that contribute strongly to reducing the manufacturing costs and make small wind turbine more competitive for energy production. The results of this analysis will enable the definition of the

configuration that produces better performance and higher annual energy production.

3. Adopt a rotational speed based on available equipments in the market and impose the compressibility limit.

The calculation process is started by assuming initial values for the axial and tangential induction factors usually considered as $a = a' = 0$, (to be corrected at the end of the iteration process), proceed to calculate the flow angle at the particular radial position of the blade segment, then calculate the angle of attack of the airfoil segment at the specific radius. From the known angle of attack and the local Reynolds number, the lift and drag coefficients can be determined from the aerodynamic characteristics of the airfoil or alternatively can be determined by using the software X-foil. From the knowledge of the lift and drag coefficients one can calculate the normal and tangential force coefficients of the segment, calculate a and a' taking into consideration the Prandtl / Glauert corrections as pointed out above, calculate and compare their numerical values. If the difference between the assumed values and the predicted ones are more than the pre-established value of 10-4, then use the new values and repeat the iteration procedure until convergence is achieved and then continue the calculation as in the block diagram. If the differences are within the pre-established limit, continue the calculation to determine the thrust, torque and power of the segment. Repeat this procedure for each segment and then integrate to determine the total torque, total normal force, and total power and their corresponding coefficients

2.2 Annual energy production

The annual energy production (AEP) is the energy produced by the wind turbine running under real wind conditions during a full year. The AEP is the combination of the production curve with a probability density function for the wind. Details of the calculations are in Burton (2001).

3. Numerical treatment

A numerical home-built code based on the BEM method and Weibull distribution elaborated for the software Matlab is used to evaluate the aerodynamic and geometrical parameters of the small horizontal axis wind turbine. The BEM method is implemented in the code because it is classical, simple and produces good results (Okita *et al.* 2018). By using this theory it is possible to calculate the steady loads, the thrust and power for different values of wind speed, rotational speed, and chord and twist angle distributions.

The nominal conditions for all the wind turbines that were analysed are presented in the Table 1. Initially, the rotor radius is estimated from Eq. (1).

$$R = \sqrt{\frac{2P}{\pi \rho \eta C_p V^3}} \tag{1}$$

However, there is an inactive part of the blade length which is used to attach the blades to the hub considered here as 15% of the rotor radius.

The geometrical characteristics of the airfoils used in this work are:

1. Gottingen 413: maximum thickness of 16.4% at 30% chord and maximum camber of 4.6% at 39.8% chord.

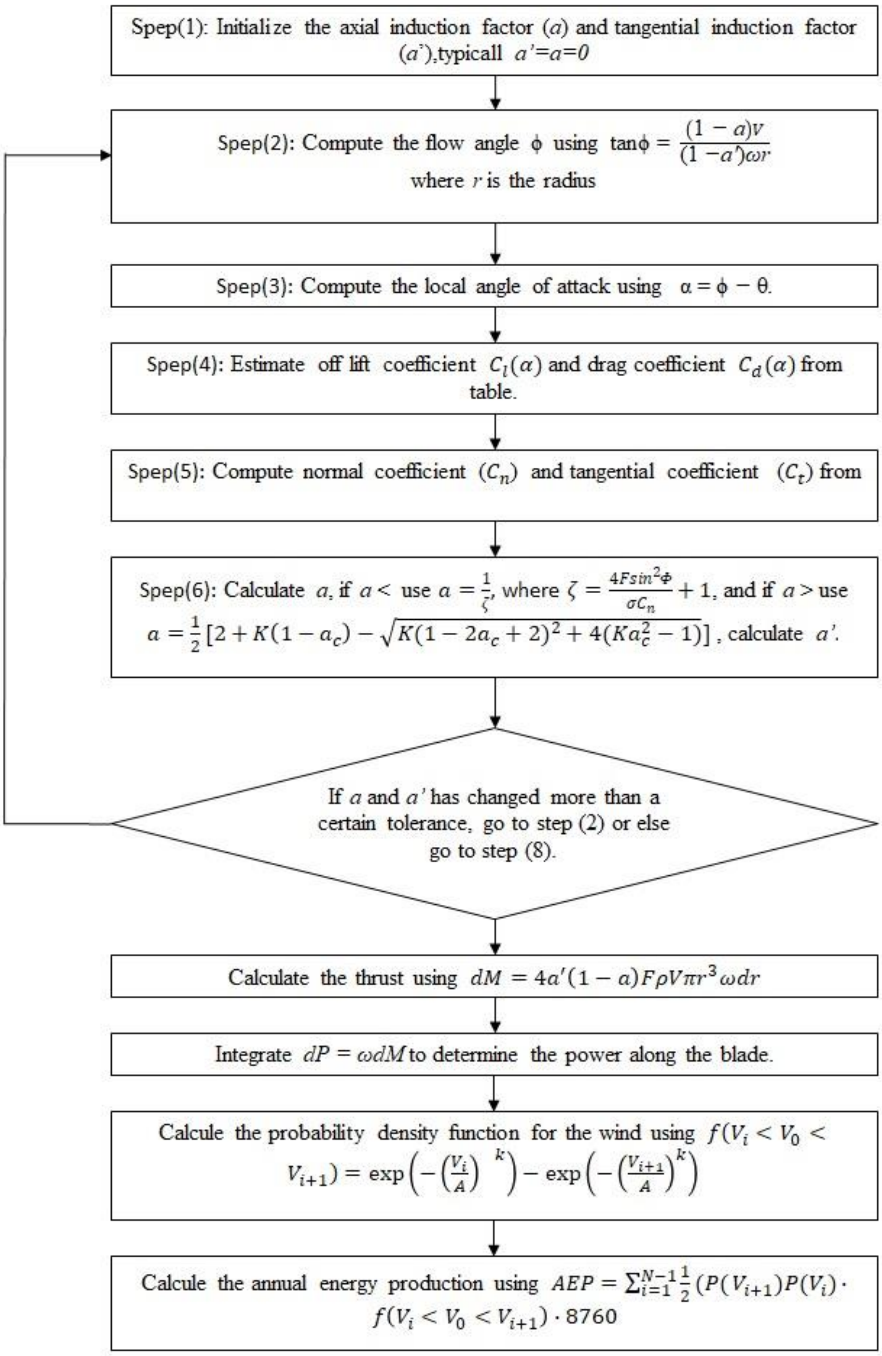


Fig. 3 Block diagram of the BEM

2. NACA 2415: maximum thickness of 15% at 29.5% chord and maximum camber of 2% at 39.6% chord.

Table 1 Nominal conditions for the present study

Parameters	Values
Power (P)	20 kW
Speed (V)	10 m/s
Air density	1.225 kg/m^3
Number of blades (B)	3
Estimated Aspect ratio	6
Estimated Power coefficient (C_p)	0.55
Estimated Tip speed ratio (λ)	9.1646
Efficiency (η)	0.90

The angular velocity is determined based on the sonic limitation

$$M = \frac{\omega R}{V_{sound}} < 0.2 \tag{2}$$

where V_{sound} is the speed of sound.

The tip speed ratio is calculated from Eq. (3)

$$\lambda = \frac{\omega R}{V} \tag{3}$$

In the present investigation the chord distribution is a parameter to be examined. To be able to investigate the effect of the chord, three different chord distributions are analyzed: constant, elliptic and linear tapered distributions. An aspect ratio of six is assumed to reduce the tip vortex effects. Therefore, the chord equations for elliptic and linear distributions are developed as below:

The elliptic chord is calculated from

$$c = 1.23798\sqrt{1 - \left(\frac{r}{R}\right)^2} \tag{4}$$

The linear tapered chord distribution is given by

$$c = 1.44533 - 0.1795\left(\frac{r}{R}\right) \tag{5}$$

The twist angle is also an investigated parameter and for this purpose the linear distributions as given by Eq. (6), where θ_{max} is considered as 22° while θ_{min} is considered as 2°. These values were chosen based on calculations realized showing relatively smooth variations.

$$\theta = \theta_{max} - \frac{\theta_{min}\,(\mathrm{n}-1)}{N-2} \quad n = 1,2,\ldots,N \tag{6}$$

With the geometry parameters initiate the BEM method following Hansen (2008) as shown in Fig. 3.

To determine the probability of occurrence of wind speed we used the wind map of the Wind Energy Atlas of the State of São Paulo (2012). Therefore, for a height of 50 m in the region of Campinas – SP, the average wind speed is 5 m/s, the form factor is 1.8 and scale factor is 5.627 m/s. From this it is possible to calculate the AEP.

3.1 Validation

Using the data in Jonkman *et al.* (2009) an additional comparison is made for the power generated against wind speed as shown in Fig. 4. One can observe the good agreement between the numerical predictions and Junkman's results. For wind speed over about 11 m/s the over-speed control system is operated in Jonkman´s work. In the present numerical study no over-speed control is included in the model.

Hernández and Crespo (1987) calculated the aerodynamic performance of a horizontal axis wind turbine and compared their predictions with experimental measurements. The experiments were carried out at low velocity on a two bladed, 1.6 m diameter wind turbine with blades based on Wortmann-FX77-W airfoil. The distributions of thickness, chord and twist angle along the blade are shown in Table 2.

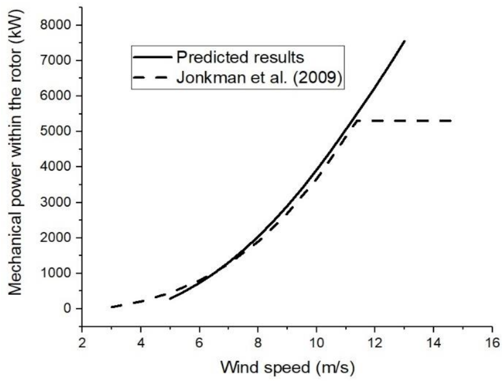
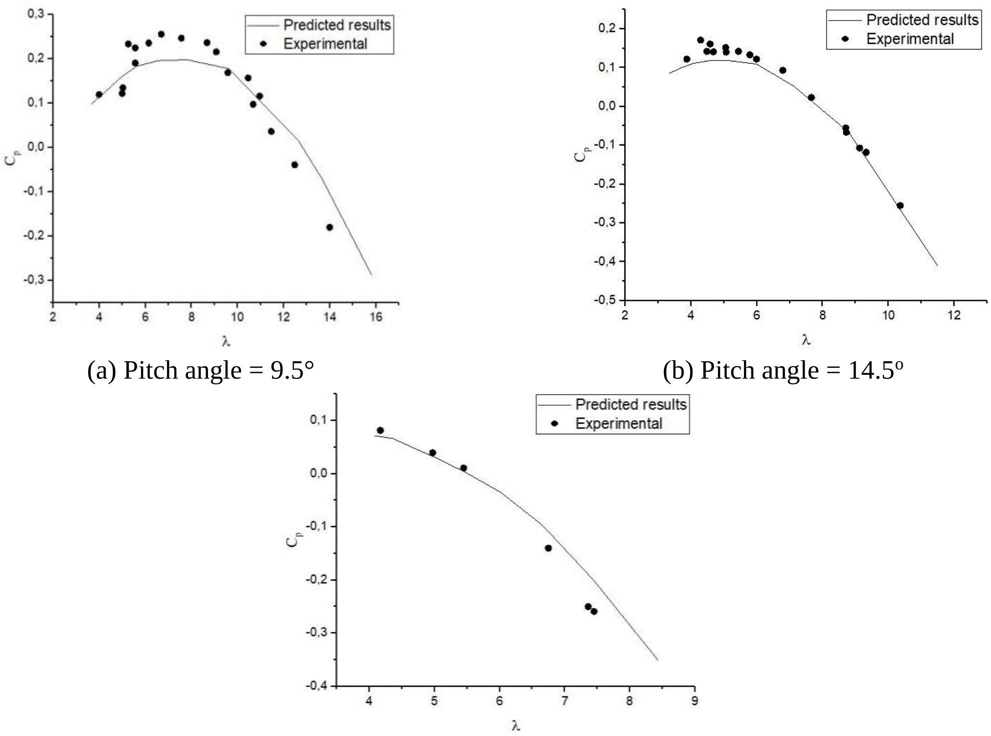


Fig. 4 Predicted Variation of mechanical power output with the wind speed, comparison of the present predictions with the results from Jonkman *et al.* (2009)

Table 2 Distributions of thickness chord and twist angle along the blade (Hernández and Crespo 1987)

Section (%)	Chord (mm)	Thickness (%)	Twist angle (degrees)
100	17.6	15	-7.5
90	21.2	15	-5.7
80	28.9	15	-3.9
70	31.4	15	-2.1
60	40.2	15	-0.3
50	47.8	15	1.4
40	60.3	18.6	3.2
30	69.1	22.2	5.0
20	75.4	25.8	6.8



(a) Pitch angle = 9.5° (b) Pitch angle = 14.5°

(c) Pitch angle = 19.5°

Fig. 5 Variation of the coefficient of power with the tip speed ratio blade (Hernández and Crespo 1987), (a) pitch angle = 9.5°, (b) pitch angle = 14.5° and (c) pitch angle = 19.5°

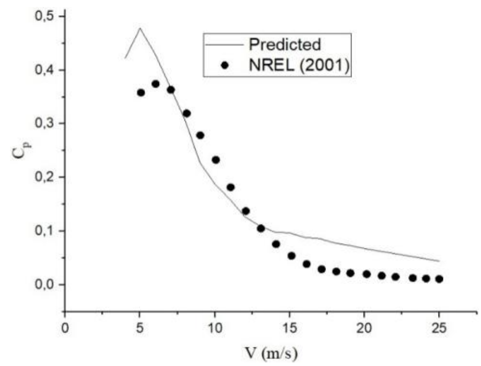


Fig. 6 Comparison between the predicted power coefficient and the experimental results of NREL (2001)

The model had a pitch control system and its axis could be oriented relative to the incident wind velocity. The wind turbine was coupled to a DC generator. The tests were carried out at different wind tunnel velocities and at a constant angular velocity of 1500 rpm. The pitch angle varied in the range from 9.5° to 19.5°. The relevant parameters from the study of Hernández and Crespo (1987) are used in the present code to produce results to be compared with the experimental findings. Fig. 5 shows good agreement between the present predictions and the experimental work of Hernández and Crespo (1987).

The National Renewable Energy Laboratory (NREL) (2001) conducted an experimental study on a twin blade horizontal axis wind turbine based on airfoil S809. The wind turbine had blade geometry as in Table 2 and is operated at constant rotational speed of 72 rpm. Fig. 6 shows the variation of the predicted power coefficient and experimental results with the wind velocity. The general trends are the same between the predicted results and experiments. The differences at low and very high wind velocities are attributed to the fact that at these ranges of Reynolds numbers and angle of attack the XFOIl failed to determine reliable lift and drag coefficients for some of these values

4. Results and discussion

In this section the different chord and twist angles distributions are incorporated in the airfoils GO 413 and NACA 2415. The effects of the chord and pitch angle distributions on the blade geometry, its aerodynamic performance and annual power production are investigated.

4.1 Effects of the chord distribution

The linear tapered, constant and elliptic chord distributions are investigated with the objective of determining their influence on the aerodynamic characteristics of the rotor.

4.1.1 Effects on the thrust

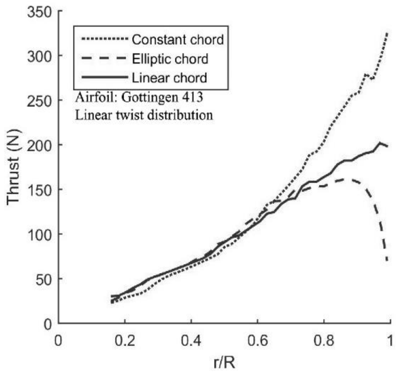
Fig. 7(a) shows the thrust distribution along the blade, for a nominal wind speed of 10 m/s, airfoil section GO 413 with linear twist distribution and for three different chord distributions. The sudden changes in the curves are due to numerical interpolation by X-foil. As one can observe the constant chord distribution produces more thrust from the root to 60% of the blade. This is due to the fact that constant distribution produces larger values of chord than the other distributions up to 60% of the blade length as shown in Fig. 7(c).

The elliptic and linear chord distribution show slightly smaller but similar distribution up to 60% of the blade followed by lower values for the rest of the blade. At the tip region, the constant chord distribution produces higher thrust than that of either the elliptic and linear chord distributions. This is due to the fact that the value of constant chord is greater than that of the elliptic and linear chord distributions at the last 40% of the blade length. This implies higher solidity ratio and consequently values of axial induction factor nearer to the Betz limit, which is 0.33. Higher thrust distribution at the tip increases the bending and tangential moments on the blade root.

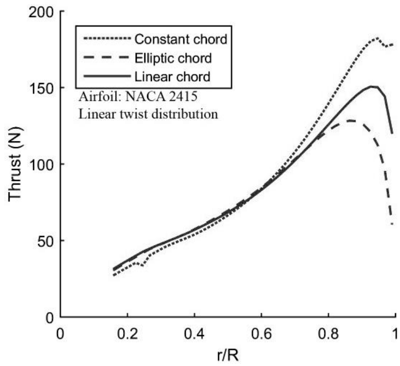
Fig. 7(b) shows the variation of thrust along the blade length for the airfoil NACA 2415 for the same three chord distributions and the linear twist angle distribution. As one can observe the behavior is the same as in the case of the GO 413 airfoil. The high thrust distribution at the tip increases the bending and tangential moments on the blade root.

4.1.2 Effects on the torque

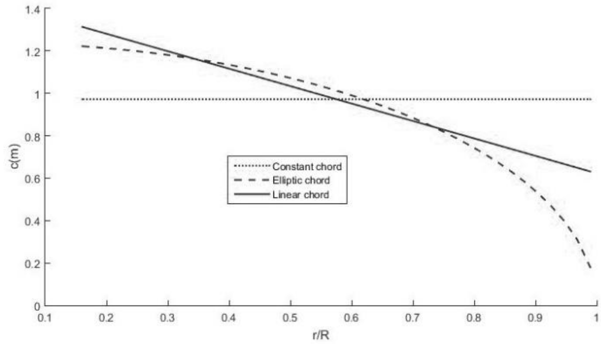
To study the effect of the chord distribution on the torque for a nominal wind speed of 10 m/s, the same chord and linear twist distributions are used for investigating the airfoils GO 413 and NACA 2415. Fig .8 shows the distribution of torque along the blade length for the three chord distributions. The decay at the blade tip is due to the increased axial induction factor in the same region. In the case of the airfoil GO 413 the linear and elliptic chord distributions are coincident



(a) Pitch angle = 9.5°

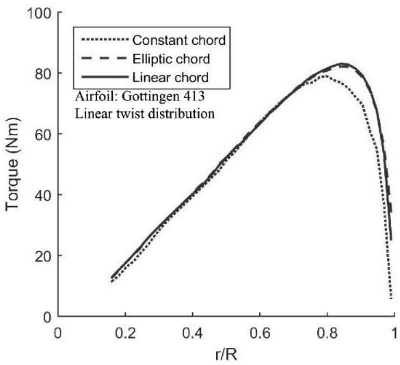


(b) Pitch angle = 14.5°

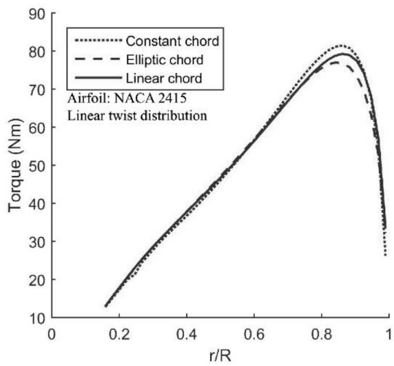


(c) Pitch angle = 19.5°

Fig. 7 Variation of thrust with the dimensionless radius, for the case of linear twist angle for the airfoils: (a) Gottingen 413, (b) NACA 2415 and (c) geometry of the investigated chord distributions



(a)



(b)

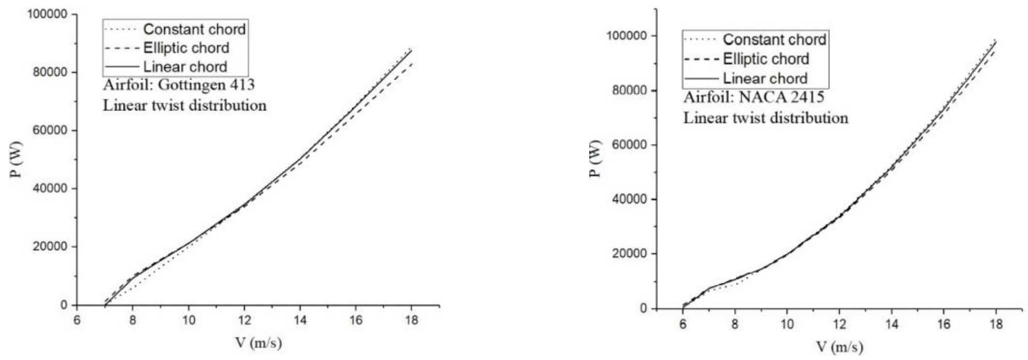
Fig. 8 Variation of the torque with the dimensionless radius for the case of linear twist angle for the airfoils: (a) Gottingen 413 and (b) NACA 2415

while the constant chord distribution is smaller. In the case of the airfoil NACA 2415 the linear distribution shows higher values of thrust near the tip region which is not desirable. The elliptic chord distribution shows the lowest values near the tip region which is beneficial from the point of view of mechanical resistance. This effect is produced mainly due to the reduced chord length near the tip imposed by the geometry.

4.1.3 Effects on power generation

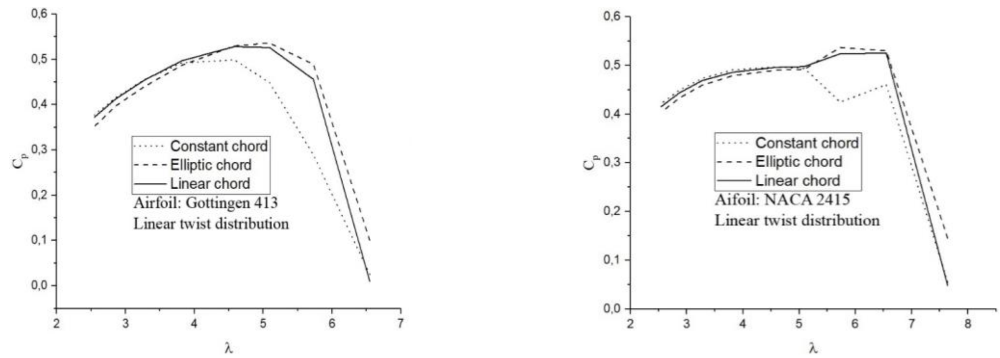
The effect of the chord distribution on the generated power is shown in Fig. 9(a) for the airfoil GO 413. As can be seen the elliptic and linear chord distribution seems to favor more generated power than constant chord distributions up to wind speed 11 m/s. While from 12 m/s upwards the constant and linear distributions seem to produce more power. Fig. 9(b) shows similar results for the case of NACA 2415 airfoil, but the elliptic and linear chord distributions seem to favor more generated power than constant chord distribution up to wind speed 10 m/s. This is because the summation of the values of the elementary torques along the blade for each wind speed is greater for the elliptic and linear chord distributions than for the constant chord distribution. The linear chord distribution sums up another advantage due to easiness of fabrication and consequently cheaper blades. Hence, one can conclude that the linear chord distribution favors more power production besides the simplicity of blade production.

For the higher wind velocity range, that is more than 10 m/s, the tendency is inverted in favor of the constant chord distribution, which generally is not acceptable for aerodynamic and mechanical reasons.



(a) (b)

Fig. 9 Variation of the generated power with wind speed for the case of linear twist angle for the airfoils: (a) Gottingen 413 and (b) NACA 2415



(a) (b)

Fig. 10 Variation of the power coefficient with the tip speed ratio for the case of linear twist angle for the airfoils: (a) Gottingen 413 and (b) NACA 2415

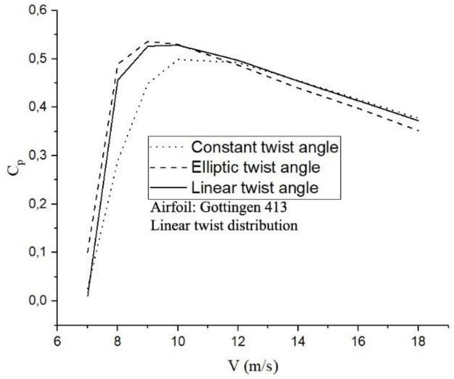
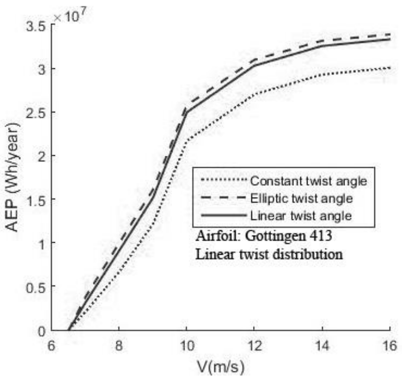
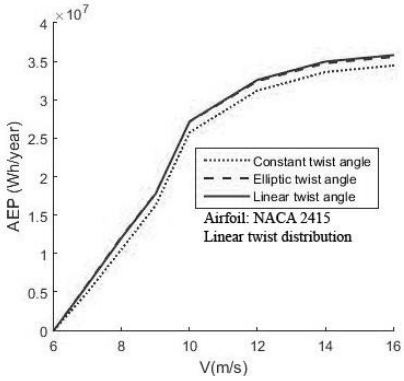


Fig. 11 Variation of the power coefficient with the wind speed for the case of linear twist angle distribution for the rotor with Gottingen 413



(a)



(b)

Fig. 12 Variation of the annual energy production with wind speed for the case of linear twist angle for the airfoils: (a) Gottingen 413 and (b) NACA 2415

4.1.4 Effects on power generation

Fig. 10(a) shows the variation of the power coefficient with the chord distribution for the airfoil GO 413. As can be seen the constant and linear chord distributions associated with the linear twist distribution show higher values of CP than that of the elliptic chord distribution up to the tip speed ratios of about 4.3. After this, the elliptic chord distribution presents the highest values of the power coefficient followed by the linear chord distribution. Fig. 10(b) for the airfoil NACA 2415 shows similar tendency except there are small differences between in CP along the tip speed ratio range.

Fig. 11 shows the variation of the power coefficient with the wind speed. One can observe that over the wide range of wind velocity the elliptic and linear tapered chord distribution show higher coefficient of power.

4.1.5 Effects on power generation

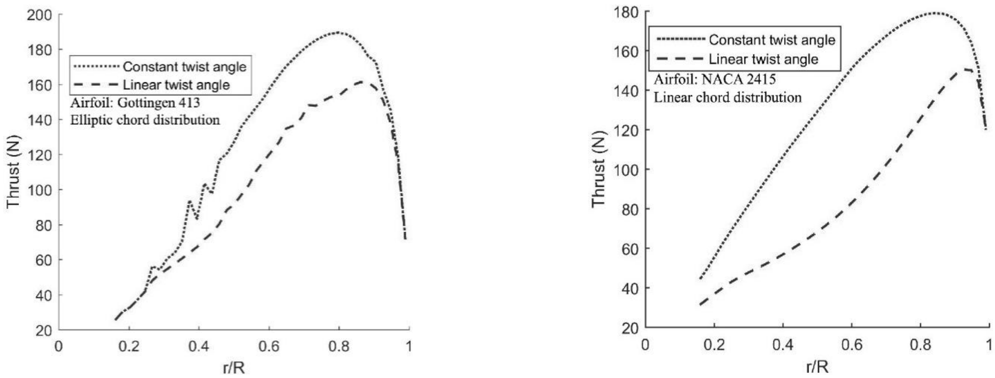
The effect of chord distribution on the annual power production (AEP) is shown in Fig. 12(a) for the case of GO 413 airfoil. One can see that the elliptic chord distribution shows slightly higher values of AEP than the other chord distributions. This behavior is valid for the linear twist angle distribution. For the NACA 2415 airfoil shown in Fig. 12(b), the linear chord distribution presents higher values of AEP. These effects are due to the fact that the elliptic and linear chord distributions produce better flow distribution that contributes to having an axial induction factor closer to Betz limit resulting in high torque and power values.

4.2 Effects of the twist angle distribution

Two distributions of twist angle are investigated, that is constant and linear twist angle distributions. The linear and elliptic chord distributions are chosen since they produced better results for the airfoils GO 413 and NACA 2415, respectively.

4.2.1 Effects on the thrust

Fig. 13 shows the thrust distribution along the blade length for the airfoils GO 413 and NACA 2415 for the two twist angle distributions for the linear and elliptic chord distributions. One can observe that the constant twist angle produces more thrust along the blade for the two airfoils. This is due to the fact that the twist angle distribution shown in Fig. 14 provides bigger angles of attack which produce high values of Cl. The apparent irregular changes are due to numerical



(a) (b)

Fig. 13 Variation of the thrust along the blade for the case of linear chord distribution for the airfoils: (a) Gottingen 413 and (b) NACA 2415

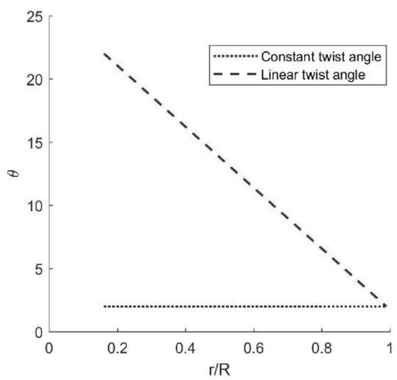


Fig. 14 Variation of the twist angle distribution along the blade length for the airfoils

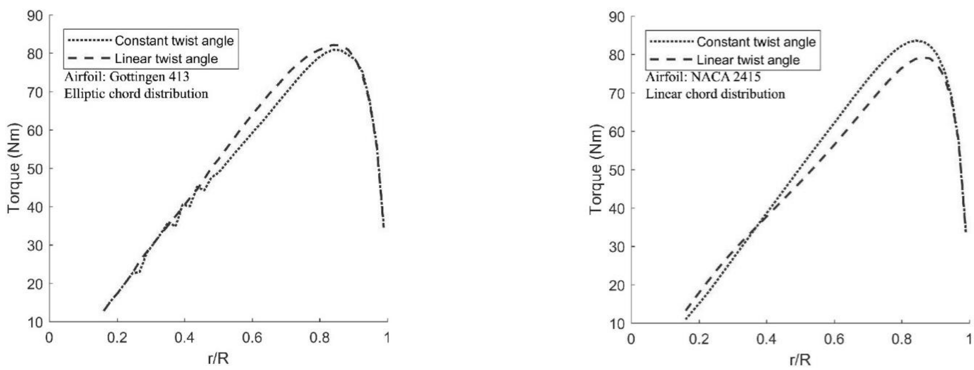
interpolation by X-foil software.

4.2.2 Effects on the torque

Fig. 15 shows the torque distribution along the blade for the airfoils GO 413 and NACA 2415 for the condition of linear chord distribution and for the two twist angle distributions. As one can observe the linear twist angle produces more torque distribution along the blade for the airfoil GO 413 and the constant twist angle produces more torque for the airfoil NACA 2415. This behavior can be explained in a similar manner as in the preceding case by using Fig. 14.

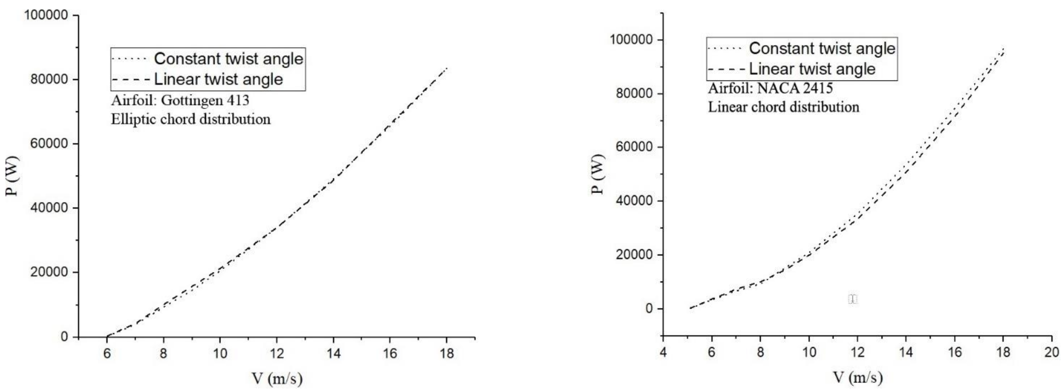
4.2.3 Effects on the generated power

Fig. 16 shows the effect of the twist angle distribution on the generated power for the two airfoils. The GO 413 with elliptic chord distribution associated with linear twist distribution shows almost equal generated power as the constant twist distribution. The NACA 2415 with linear chord distribution associated with constant twist distribution shows higher generated power than the linear distribution. This is because the torque is higher in this range of wind speed.



(a) (b)

Fig. 15 Variation of the torque with the dimensionless radius for the case of linear chord distribution for the airfoils: (a) Gottingen 413 and (b) NACA 2415



(a) (b)

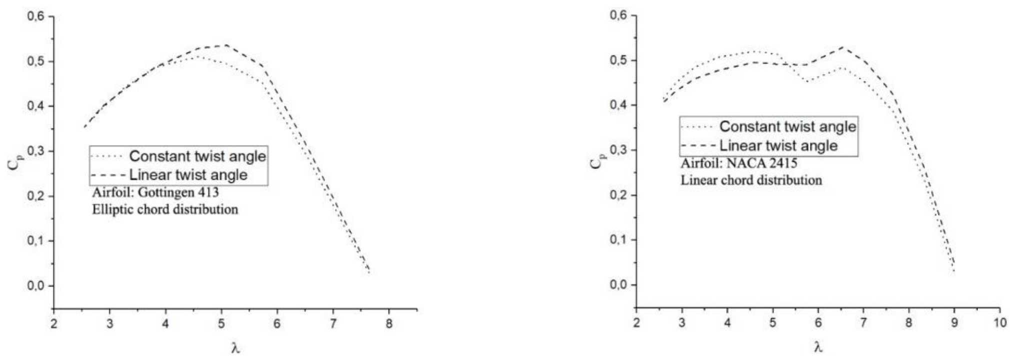
Fig. 16 Variation of the generated power with the wind speed in the case of linear chord distribution for the airfoils: (a) Gottingen 413 and (b) NACA 2415

4.2.4 Effects on the power coefficient

Fig. 17(a) shows the variation of the power coefficient for the two twist angle distributions for GO 413 where the linear twist angle indicates better values of Cp in the range of tip speed ratio of 3.8 to 7.6. This is due to the fact that the distribution of twist angle affects the distribution of the angle of attack along the blade and hence increases the aerodynamic performance of the blade section when the local angle of attack is bigger. Fig.17(b) shows the variation of the power coefficient with the twist angle distribution for NACA 2415. The results indicate that constant twist angle produces higher values of Cp in the range of tip speed ratio of 2.55 to 5.1, while linear twist angle is higher in the range of tip speed ratio of 5.1 to 9.

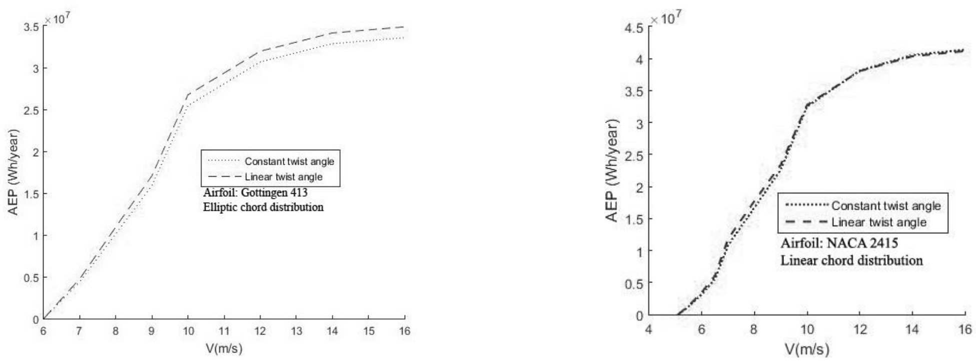
4.2.5 Effects on the annual power production (AEP)

The effect of the twist angle distribution on the annual energy production (AEP) is shown in Fig. 18(a) for the case of GO 413 airfoil. One can observe that the linear twist angle distribution shows higher values of AEP. This effect is due to the fact that the power produced for the case of linear twist is more than that produced by the constant distribution of twist angle, which is again dependent of the local angle of attack. Fig. 18(b) shows that the linear twist angle for NACA 2415 airfoil produces nearly the same AEP as that of the constant twist angle.



(a) (b)

Fig. 17 Variation of the power coefficient with the tip speed ratio for the case of linear chord distribution for the airfoils: (a) Gottingen 413 and (b) NACA 2415



(a) (b)

Fig. 18 Variation of the annual energy production with the wind speed for the case of linear chord distribution for the airfoils: (a) Gottingen 413 and (b) NACA 2415

5. Conclusions

A home built numerical code based on the Blade Element Momentum method is implemented in Matlab and validated against available numerical and experimental results showing good agreement. The code is used to identify the airfoil section and the optimum chord and blade twist angle distribution that produce maximum annual energy. Three chord distributions (constant, elliptic and linear) and two twist angle distributions (constant and linear) are investigated and their effects on the resulting torque, thrust and power are evaluated.

The analysis of chord effects showed that the greater the chord the greater the thrust. Moreover, the results showed higher torque distribution along the blade for Gottingen 413 with elliptic chord while NACA 2415 with linear chord produced more power and consequently more annual energy.

The analysis of twist angle distribution showed high values thrust for constant twist angle for both airfoils. The torque distribution was best for Gottingen 413 when using linear twist angle and for NACA 2415 when using constant twist angle, generating more power and annual energy production.

The results showed that NACA 2415 airfoil section with elliptic chord and constant twist angle distributions are the parameters that produced the highest annual energy production.

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