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Aerodynamic Performance Assessment of Wind Turbine Composite Blades Using Corrected Blade Element Momentum Method

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ABSTRACT

Aerodynamic loads for MW scale horizontal wind turbine blades are calculated and analysed in this paper. The blade element momentum (BEM) method is employed for analysing the performance of wind turbine blades. However, research shows that the thrust coefficient predicted by BEM method is significantly from the experimental data, when the value of axial induction factor is greater than 0.4. To solve this problem and to increase the accuracy of the prediction, some correction models such as Glauert's and Shen's approaches should be utilised in the equations of thrust coefficient with loss factor. A numerical example of Sandia SNL100-00 wind turbine blade is adopted to estimate the aerodynamic performance under various wind speeds. Three different BEM methods are discussed, including the BEM method without correction, with Prandtl-Glauert's correction and with Shen's correction. The predicted curves for a wide range of wind speeds obtained from different BEM models are compared with the results by QBlade, which is an open source software for wind turbine analyses. The results show that the BEM method with Shen's correction gives the best correlation to the data of QBlade, which are useful for analysing the aerodynamic performance of wind turbine blades.

1. INTRODUCTION

With the increasing energy consumption in the world, renewable and clean energy such as wind resource has been considered as an alternative way to resolve the energy crisis. Energy crisis and greenhouse effect have led to an increasing demand for clean energy. Among them, the wind is the most cost-effective and feasible energy, and thus it has been a very attractive option for utilities, independent power producers and companies (Chen and Zhang 2017). In the wind turbine system, the most critical component is the wind turbine blades since the manufacturing cost of the blades is approximately 15-20% of the total manufacturing cost, and their maintenance

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cost is about 25-30% of the wind turbine production cost (Florian and Sørensen 2015). In order to improve the performance of blades in offshore wind turbines, layered fibre-reinforced polymer composite materials are usually adopted for the large blades since these materials have better mechanical properties such as higher fatigue resistance and lighter weight, compared with traditional homogeneous materials i.e. metals (Zhang *et al.* 2016, Zhang and Chen 2016). One challenge in structural damage estimation is that the wind turbine blades are under complex load conditions, such as aerodynamic load, gravitational load, inertial loads and operational loads (Wang *et al.* 2014). Among these loads, the aerodynamic loads are significantly affected by wind speed in environmental condition since the spectrum of wind speed is in high frequency and amplitude. It is important to develop a method for accurately analysing the aerodynamic loads in order to obtain the performance of wind turbine blades. According to this method, the performance analysis can be used to plan the maintenance strategies, which may prevent the failure of the entire wind turbine.

For aerodynamic load calculation of blade, the blade element momentum (BEM) method is recognised as the simplest method, and is still widely used for practical engineering applications of wind turbine blades (Dai *et al.* 2011, Tahani *et al.* 2017, Wang *et al.* 2014). It offers the possibility to perform fluid dynamics design of rotor blades, and to evaluate wind turbine performance in on-design and off-design conditions (Vaz *et al.* 2011). With the implementation of this model it is possible to design the rotor, to choose the geometric characteristics of the turbine, such as rotor diameter, aerodynamic airfoils, chord, pitch and twist, and to evaluate the forces acting on the blades, as well as the thrust, torque and the power at each rotor element. With this mathematical model, it is also possible to evaluate turbine performance with a wide range of wind velocities. The BEM theory is based on the Glauert (1926), modified for application to wind turbines. In recent years the BEM theory has been optimised and modified to provide increasingly accurate results such as Spera (1994), Buhl Jr (2005), and Shen *et al*. (2005).

This study presents a method for investigating the performance of a composite wind turbine blade based on BEM method with correction. Three different BEM methods are discussed, i.e. the BEM method without correction, with Prandtl-Glauert's correction, and with Shen's correction. These BEM methods are used for calculating aerodynamic loads for a range of wind speeds, and then the results are compared with the data by software QBlade. A numerical example of Sandia SNL100-00 wind turbine blades (Griffith and Ashwill 2011, Jonkman *et al.* 2009) is investigated to estimate the performance under various wind speed by proposed method. The predicted curves for various wind speeds obtained from each BEM models are compared with the results of QBlade, which is an open source wind turbine analysis software. It has been shown that the BEM method with Shen's correction gives the best correlation with the data of QBlade. From the results, the proposed method can both provide a useful tool for evaluating the performance of wind turbine blade and assess structural performance of the wind turbine blades with a wide range of wind velocities.

2. BLADE ELEMENT MOMENTUM METHOD

The BEM method is one typical theory to analyse the performance of wind turbine aerodynamics on the blades. It treats the revolving rotor as an actuator disc that combines blade element theory and one-dimensional momentum theory in both the rotor axial and tangential direction. Both rotor axial and tangential induction factors that describe the airflow speed change are introduced in the one-dimensional momentum method to calculate the wind thrust and rotor motivation torque (Dai *et al.* 2011). The blade element theory separates the blade into several elements and ignores the mutual influence between two adjacent elements. The aerodynamic loads on each element are dependent on its local airfoil characteristics, i.e. the lift and drag coefficients.

The BEM method is widely used in recent studies for wind turbine blade (Vaz *et al.* 2011, Tahani *et al.* 2017, Wang *et al.* 2014). From the one-dimensional momentum method, axial and tangential momentums for each element are described as below (Manwell *et al.* 2010)

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

$$dQ = 4\pi r^3 \rho a'(1-a)V_0 \Omega f dr \tag{2}$$

where dT and dQ are thrust and torque for each element. In the above equations, V_0 is free stream velocity, r is radial location along the blade length, Ω is angular velocity, a and a' are axial and tangential induction factor, respectively.

From the blade element theory, thrust T and torque Q are determined as follows

$$dT = \frac{1}{2}B\rho {V_{vel}}^2(C_l cos\varphi + C_d sin\varphi)cdr \tag{3}$$

$$dQ = \frac{1}{2}B\rho {V_{vel}}^2(C_l sin\varphi - C_d cos\varphi)cdr \tag{4}$$

where B is the number of the blades, ρ is the air density, C_l and C_d are lift and drag coefficients at the local angle of attack α, respectively, V_{vel} is local resultant air velocity, c is chord.

The local angle of attack α is given by

$$\alpha = \varphi - \theta \tag{5}$$

where the θ is the local pitch of the blade, and φ is the angle between the plane of rotation and the relative velocity, which can be expressed as

$$tan\varphi = \frac{(1-a)Vo}{(1+a')\Omega r} \tag{6}$$

The torque and thrust forces depend on the tangential and axial induction factors. To evaluate them it is necessary to implement the momentum and angular momentum conservation equations.

From the conservation of the momentum in the axial direction, it is possible to obtain two further expressions for the thrust force dT and the torque dQ. Equalising these two Eq. (3) and Eq. (4), with Eq. (1) and (2) respectively, it is possible to obtain

$$a = \frac{1}{\frac{4sin^2\varphi}{\sigma(C_l cos\varphi + C_d sin\varphi)} + 1} \tag{7}$$

and

$$a' = \frac{1}{\frac{4sin\varphi cos\varphi}{\sigma(C_l sin\varphi - C_d cos\varphi)} + 1} \tag{8}$$

where σ is the rotor solidity, defined as

$$\sigma = \frac{Bc}{2\pi r} \tag{9}$$

The relationship between thrust coefficient C_t and axial induction a in BEM method can be expressed as

$$C_t = 4a(1 - a) \tag{10}$$

In this study, this BEM method without correction is called the traditional BEM method.

3. CLASSICAL CORRECTION OF BEM METHOD

The blade element momentum (BEM) method often calculates the value of thrust coefficient in aerodynamic loads. However, thrust coefficient predicted by the BEM method does not agree with the experimental data when the value of axial induction factor is greater than approximately 0.4. In addition, there is some loss among tip and hub in wind turbine blade. To solve this problem and to increase the accuracy of the prediction, various corrections based on the BEM method considering tip and hub loss are investigated in recent studies to obtain the relationship between axial induction factor *a* and thrust coefficient *Ct*.

3.1 Prandtl loss correction

Because of the different air pressure between the upwind surface and downwind surface, the wind will change the direction of the tip and hub, leading to an aerodynamic loss. The accuracy of the BEM method can be improved by considering the total loss factor, which is a combination of tip and hub loss factor. The most straightforward one used for the BEM method is Prandtl's tip and hub loss correction models. For a rotor with a finite number of blades in wind turbine system, the vortex system in the wake is different from a rotor with an infinite number of blades. Prandtl (1923) corrected the assumption of an infinite number of blades and derived a correction factor *F* to equations, including both tip loss F_t and hub loss F_h.

The tip loss factor F_t is expressed as

$$F_t = \frac{2}{\pi}\arccos(e^{-\frac{B(R-r)}{2rsin\varphi}}) \tag{11}$$

Due to the longer length of chord near the hub, the aerodynamic loads are also influenced by the changed wind pressure surface. Similarly, the hub loss factor F_h by Prandtl is expressed as

$$F_h = \frac{2}{\pi}\arccos(e^{-\frac{B(r-R_{hub})}{2R_{hub}sin\varphi}}) \tag{12}$$

Therefore, the total Prandtl's loss is expressed as

$$F = F_t F_h \tag{13}$$

The Eq. (6) and (7) can be corrected as

$$a = \frac{1}{\frac{4Fsin^2\varphi}{\sigma(C_l cos\varphi + C_d sin\varphi)}+1} \tag{14}$$

and

$$a' = \frac{1}{\frac{4Fsin\varphi cos\varphi}{\sigma(C_l sin\varphi - C_d cos\varphi)}+1} \tag{15}$$

The C_t in BEM method with Prandtl's loss correction can be corrected as

$$C_t = 4a(1-a)F \tag{16}$$

3.2 Glauert correction for high values of a

When the axial induction factor becomes larger than approximately 0.4, the simple momentum theory completely breaks down. Glauert (1926) gives the empirical relations between the thrust coefficient and lift coefficients can be made to fit with measurements. One last expression is found in Spera (1994), and the axial induction factor is

$$a = \begin{cases} \frac{1}{\frac{4Fsin^2\varphi}{\sigma(C_l cos\varphi + C_d sin\varphi)}+1} & a \le a_c \\ \frac{1}{2}[2 + K(1-2a_c) - \sqrt{[K(1-2a_c)+2]^2 + 4(Ka_c{}^2 - 1)]} & a > a_c \end{cases} \tag{17}$$

where $K=(4Fsin^2\varphi)/\sigma(C_l cos\varphi+C_d sin\varphi)$ and a_c equals 0.2 in this correction.

Therefore, the thrust coefficient in Glauert correction by Shera can be expressed as

$$C_t = \begin{cases} 4a(1-a)F & a \le a_c \\ 4(a_c{}^2 + (1-2a_c)a)F & a > a_c \end{cases} \tag{18}$$

In most studies, both Prandtl's loss correction and Glauert's equation are considered and used for analysing the performance of wind turbine blades. In this study, this method is called the BEM method with classical correction.

4. NEW CORRECTION OF BEM METHOD

4.1 Shen's loss correction

Shen *et al.* (2005) corrected both the induced velocities and the mass flux for tip loss effects. However, Shen corrected the lift coefficients by introducing the correction factor, F_{t1}, which has a similar form to F_t.

$$F_{t1} = \frac{2}{\pi}\arccos(e^{-g\frac{B(R-r)}{2r\sin\varphi}}) \tag{19}$$

The function, *g*, generally depends on tip speed ratio λ and the number of blades *B* as well as the chord distribution and pitch angles (Clifton-Smith 2009). However, Shen gives a simplified function dependent only on the number of blades *B* and the tip speed ratio *λ* by using the experimental data, expressed as

$$g = e^{-0.125(B\lambda-21)} + 0.1 \tag{20}$$

Similarly, the Shen's hub loss factor F_{h1} can be expressed as

$$F_{h1} = \frac{2}{\pi}\arccos(e^{-g\frac{B(r-R_{hub})}{2R_{hub}\sin\varphi}}) \tag{21}$$

4.2 Shen's correction for high values of a

Shen also considered the high value of axial induction factor where the BEM method is not suitable. Therefore, the local thrust coefficient is replaced by a linear relationship when the axial induction factor *a* exceeds the critical value (Pratumnopharat and Leung 2011).

$$a = \begin{cases} \dfrac{1}{\dfrac{4F\sin^2\varphi}{\sigma(C_l\cos\varphi+C_d\sin\varphi)}+1} & a \le a_c \\ \dfrac{2+Y_1-\sqrt{4Y_1(1-F)+Y_1{}^2}}{2(1+FY_1)} & a > a_c \end{cases} \tag{22}$$

where $Y_1=(4F\sin^2\varphi)/\sigma F_{t1}(C_l\cos\varphi+C_d\sin\varphi)$ and a_c equals 1/3 in Shen's correction.

Therefore, the thrust coefficient by Shen's correction can be expressed as

$$C_t = \begin{cases} 4a(1-aF)F & a \le a_c \\ 4(a_c{}^2F+(1-2a_cF)a)F & a > a_c \end{cases} \tag{23}$$

The Shen's correction is treated as a new correction of the BEM method for comparison in this study.

5. COMPARISONS AND ITERATIVE PROCEDURE

Figures 1 and 2 show the relationships between thrust coefficient C_t and axial induction factor *a* by above three different BEM methods when the loss factor *F* equals 1 and 0.9, respectively. It is obvious the Prandtl-Glauert correction is more sensitive to the loss factor *F*. Compared with experimental data obtained from Moriarty and Hansen (2005), the Shen's correction shows the best agreement. The BEM method without correction gives trend deviating dramatically from experimental data when the axial induction factor becomes larger than approximately 0.4.

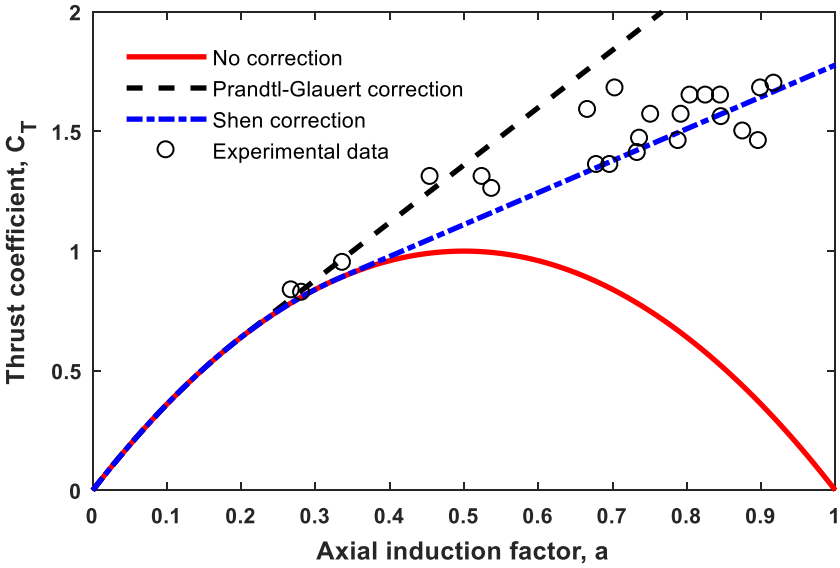

Fig. 1 Comparison between three proposed BEM methods and experimental data for F=1

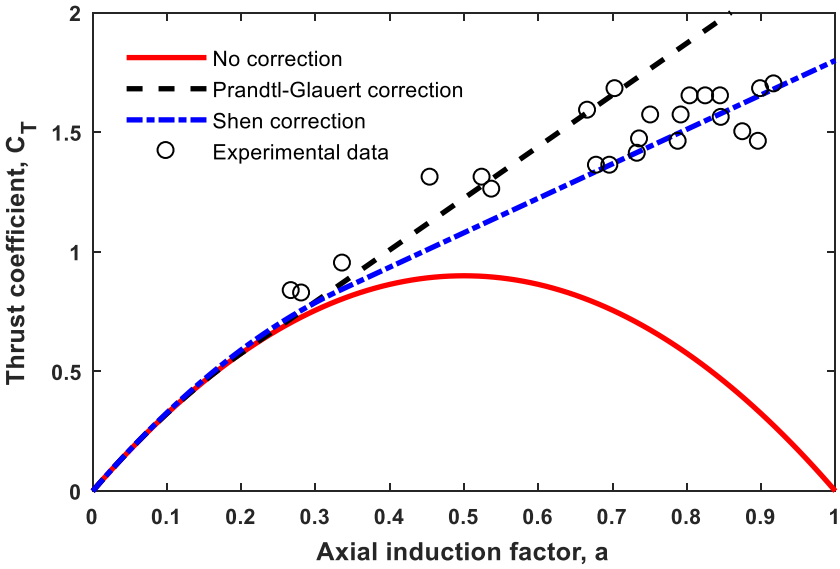

Fig. 2 Comparison between three proposed BEM methods and experimental data for F=0.9

For the BEM model, the algorithm can be summarised as the seven steps below. Since the different control volumes are assumed to be independent, each element can be treated separately and the total force can be accumulated for the whole blade (Pratumnopharat 2015, Lanzafame and Messina 2007).

Step (1) Initialise a and a', typically $a = a' = 0$.
Step (2) Compute the flow angle φ using Eq. (6).
Step (3) Compute the local angle of attack using Eq. (5).
Step (4) Read the C_l (α), C_d (α) and $C_{M1/4}$ (α) from the airfoil data.
Step (5) Calculate a and a' from each proposed BEM methods.
Step (6) If a and a' has changed more than a certain tolerance, go to step (2) or else finish.
Step (7) Compute the local loads on the segment of the blades.

Finally, the power P of the wind turbine blade is expressed as $P=\int \Omega dQ=\Omega Q$ and the maximum bending moment is $M=\int r dT$.

5. NUMERICAL EXAMPLE

In order to assess the accuracy of the performance analysis of the above methods, the 13.2 MW SNL100-00 blade developed by the Sandia is used as the reference model. This composite blade is the same geometry to the SNL100-00 reference wind turbine composite blade (Griffith and Ashwill 2011). The 13.2 MW SNL100-00 reference wind turbine is a conventional three-bladed upwind turbine based on the Sandia report (Griffith and Ashwill 2011). The Sandia SNL100-00 reference wind turbine is adopted for this case study because the corresponding detailed parameters

are available. The gross properties and control strategies of this turbine are shown in Table 1, which are the designed data for structural analysis (Griffith and Ashwill 2011).

Table 1 The gross properties of Sandia SNL100-00 13.2 MW wind turbine blade

Parameters	Value
Rating	13.2 MW
Blades No.	3
Rotor diameter, hub diameters and height	205m, 5m, 120
Cut in and out wind speed	5m/s, 25m/s
Rotor speed	7.44 rpm
Pitch angle	3 degree
Company	Sandia

The aerodynamic properties of this model, e.g., airfoil type, chord length, and twist angle, are listed in Table 2 (Griffith and Ashwill 2011). Also, in order to verify the methods presented in this research, the specifications for the reference model are introduced using the same input parameters for the Sandia SNL100-00 13.2 MW blade design data above.

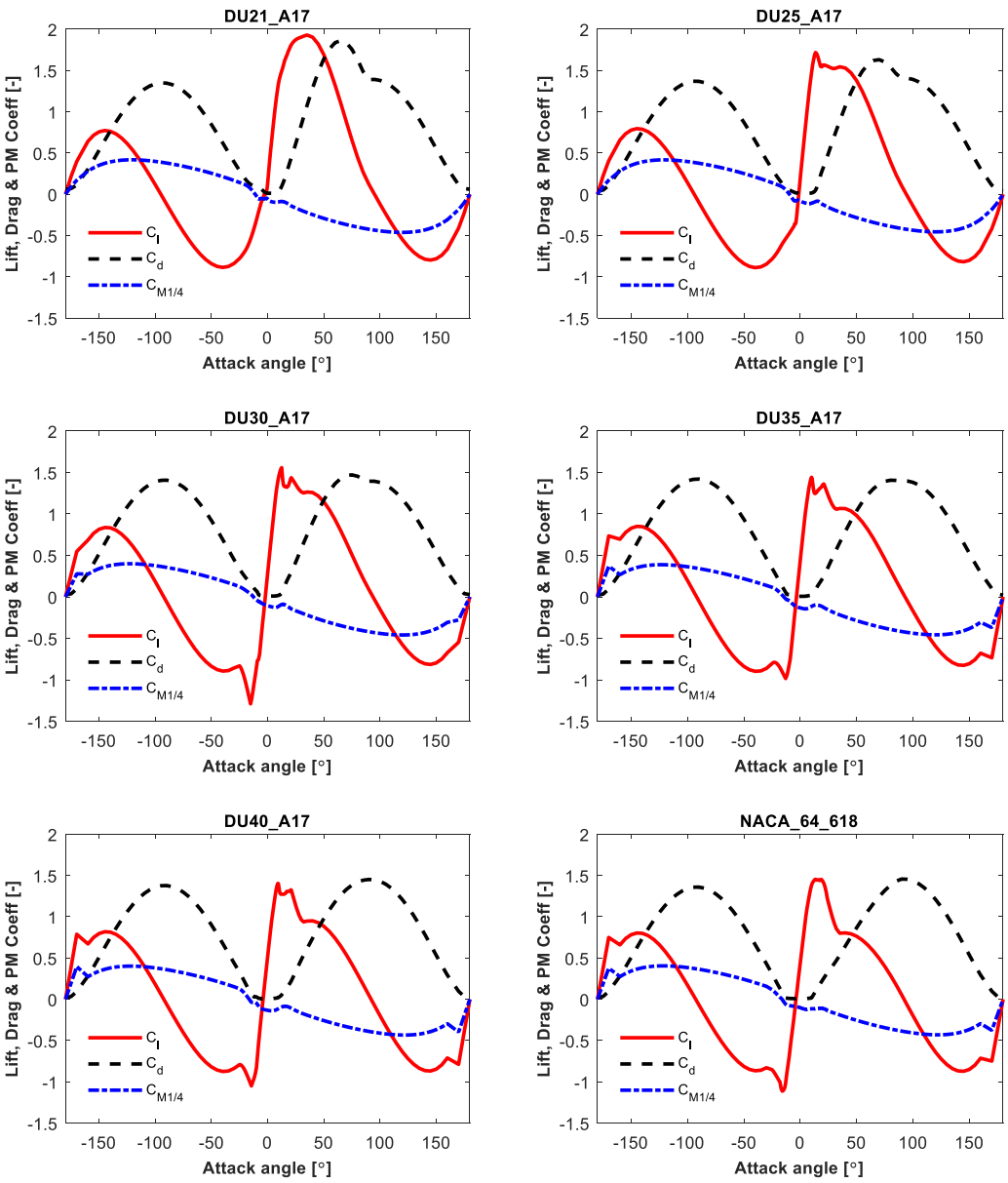

Fig. 3 Aerodynamic coefficients of the airfoils in Sandia SNL100-00 13.2 MW wind turbine blade

In order to obtain static power curve of the blade for comparing the results under same conditions, aerodynamic data of airfoils proposed in Jonkman *et al.* (2009) are used. With this information, aerodynamic performance analysis under normal conditions by BEM method is carried out. Figure 3 shows the aerodynamic coefficients of the different airfoils under the attack angles.

Table 2 Aerodynamic properties of Sandia SNL100-00 13.2 MW wind turbine blade

Section	Position [m]	Chord [m]	Twist [°]	Airfoil
1	4.4445	6.026	13.308	Cylinder1
2	8.8889	6.544	13.308	Cylinder1
3	13.3333	7.042	13.285	Cylinder2
4	17.1134	7.454	13.089	DU40_A17
5	21.8900	7.569	12.223	DU40_A17
6	26.6667	7.367	10.847	DU35_A17
7	33.3333	7.050	9.586	DU35_A17
8	39.9999	6.671	8.403	DU30_A17
9	46.6666	6.252	7.169	DU25_A17
10	53.3333	5.835	5.952	DU21_A17
11	59.9999	5.427	4.774	DU21_A17
12	66.6667	5.019	3.656	NACA_64_618
13	73.3334	4.611	2.722	NACA_64_618
14	79.9999	4.203	1.922	NACA_64_618
15	86.6667	3.829	1.194	NACA_64_618
16	91.1111	3.431	0.616	NACA_64_618
17	95.5556	2.401	0.238	NACA_64_618
18	100.0000	0.798	0.000	NACA_64_618

A blade geometry model is generated by connecting 18 airfoils, which smooths the transition from section to section and reduce the stress concentration, is shown in Fig. 4.

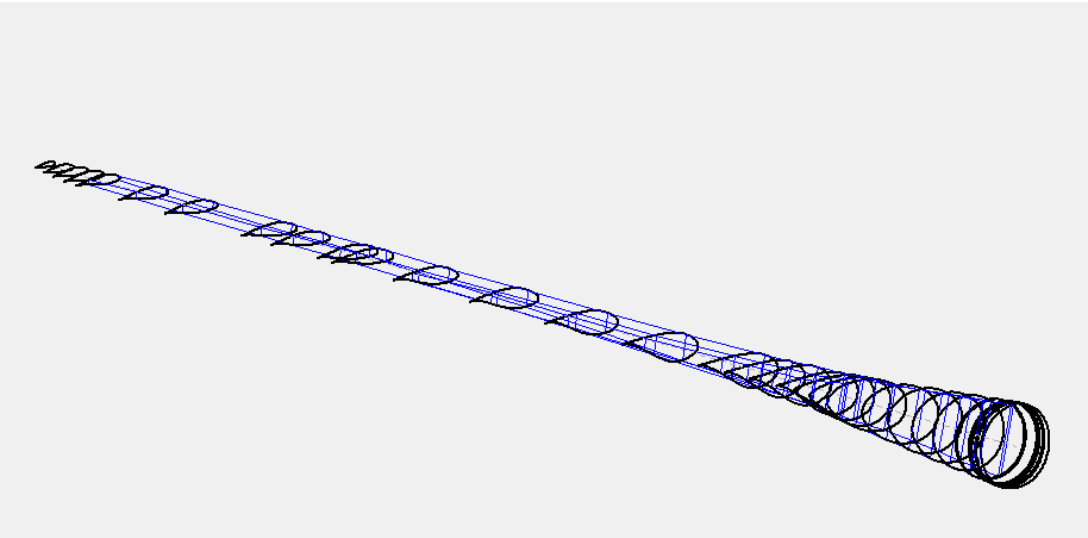

Fig. 4 Structural design of wind turbine blade of Sandia SNL100-00 13.2 MW based on the Sandia report

Since the cut-in wind speed is 5 m/s and the cut-out wind speed is 25 m/s, three different BEM methods are used in the Sandia SNL100-00 13.2 MW wind turbine blade in order to obtain the aerodynamic loads. The thrust, torque, power and maximum bending moment along with global coordinate of the blade are calculated in each element of wind turbine blade for different wind speeds, and then are compared with the data generated by QBlade software. The QBlade is a famous wind turbine performance software, which is widely used in the design of wind turbine in the world. Therefore, the data generated by QBlade are reliable and can be used for verifying the proposed three BEM methods.

Figures 5-8 show the thrust, torque, power and maximum bending by three different BEM methods and data generated by QBlade between cut-in and cut-out wind speed moment for Sandia SNL100-00 wind turbine blade. All the performance predictions of wind turbine blade by three BEM methods have the same trend. From the results, the thrust, torque, power and maximum bending moment grows quickly and then becomes stable after reaching the design wind speed. This is because the wind turbine needs to keep the stable wind rotor speed in order to produce stable power. All BEM methods give similar results with some small differences.

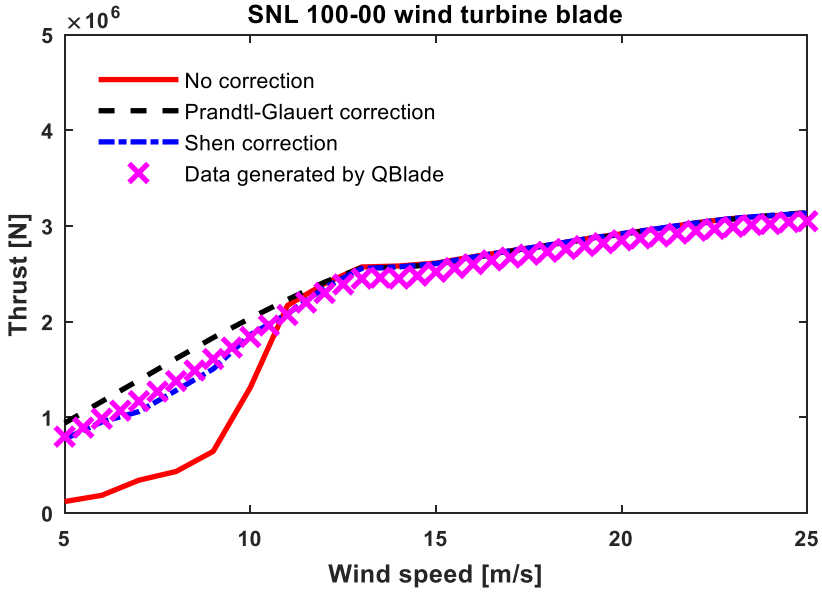

Fig. 5 Predicted thrust for Sandia SNL100-00 wind turbine blade by three different BEM methods and data generated by QBlade between cut-in and cut-out wind speed

From the results, both the classical correction and Shen's correction based on the BEM methods agree well with the QBlade data, and Shen's correction has better correlations among three BEM methods. Also, the traditional BEM method without correction has a big difference when the wind speed is low. When the wind speed is low, the axial induction factor is higher, leading to significant difference, due to the problem of high axial induction factor in the traditional BEM method.

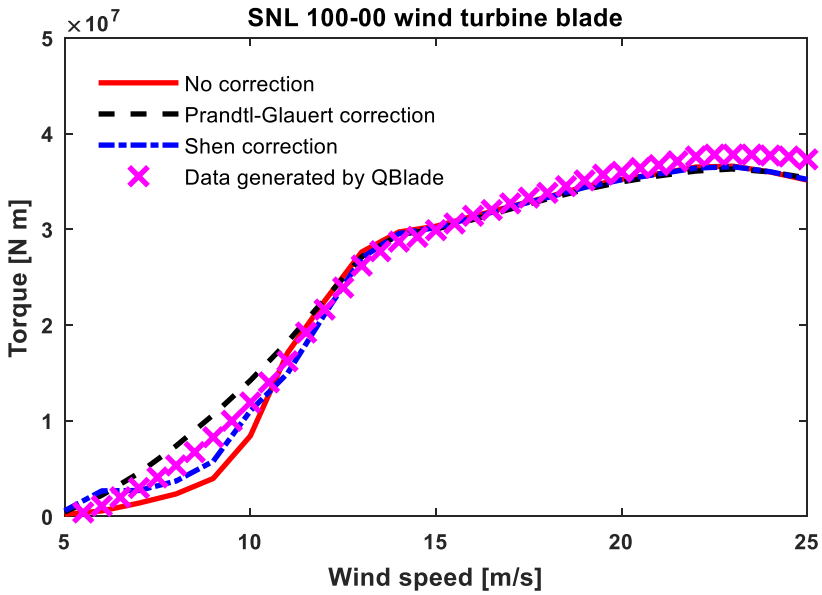

Fig. 6 Predicted torque for Sandia SNL100-00 wind turbine blade by three different BEM methods and data generated by QBlade between cut-in and cut-out wind speed

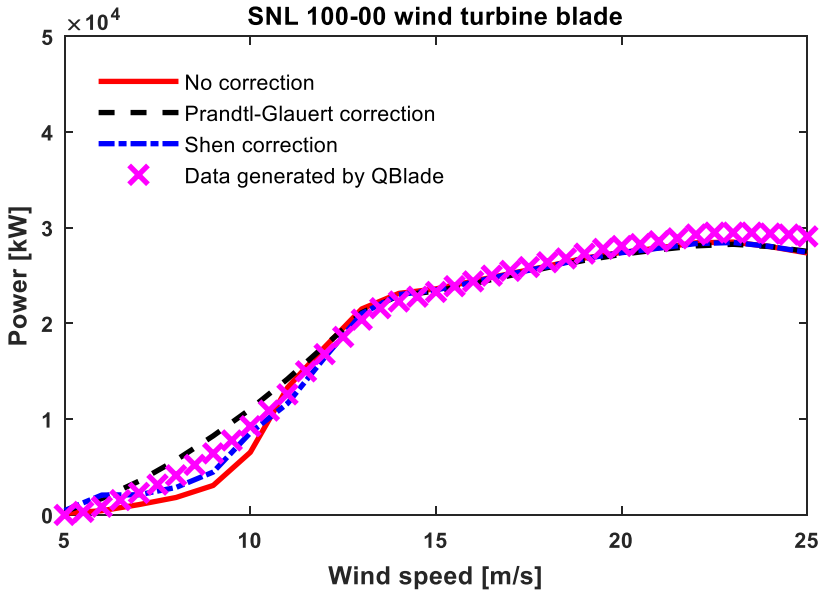

Fig. 7 Predicted power for Sandia SNL100-00 wind turbine blade by three different BEM methods and data generated by QBlade between cut-in and cut-out wind speed

The results by BEM methods with classical correction and Shen's correction are more reasonable since it considers the real situation. The traditional BEM method is not suitable for the high value of the axial induction factor *a*. Therefore, the results in low wind speed by the traditional BEM method is lower than the BEM method with classical correction and Shen's correction. As wind speed increases, these three curves follow the data generated by QBlade. Therefore, it is clear that the results of Shen's correction can be used to analyse the performance of wind turbine blade since the differences between data and Shen's correction is less than other two methods.

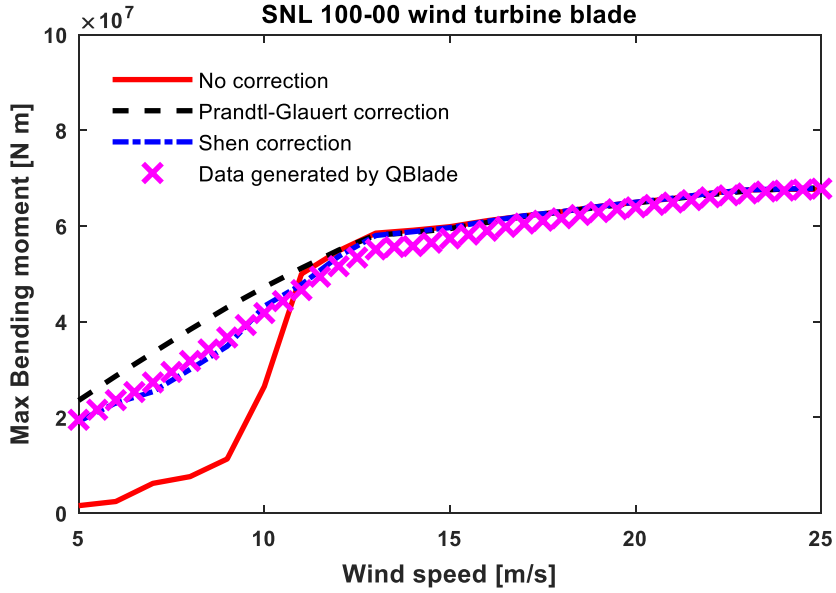

Fig. 8 Predicted maximum bending moment for Sandia SNL100-00 wind turbine blade by three different BEM methods and data generated by QBlade between cut-in and cut-out wind speed

6. CONCLUSIONS

In this study, the aerodynamic loads were estimated by traditional BEM method and corrected BEM methods such as the BEM method with classical correction and Shen's correction, and then the results are compared with the data generated by software QBlade. By considering tip and hub loss with high axial induction factor, the corrected BEM methods for the performance assessment of wind turbine blades provide useful results. From the results of the case study, the Shen's correction is the most suitable method for analysing the performance of wind turbine blades, such as the values of the thrust, torque, power and maximum bending moment.

A numerical example of Sandia SNL100-00 wind turbine blades by Sandia National Laboratories for a design of an all-glass 100 m blade for a 13.2 MW horizontal axis wind turbine is employed to estimate the performance under various wind speeds by three different methods. Based on these BEM methods and data by QBlade, the thrust, torque, power and maximum bending moment between cut-in and cut-out wind speed are estimated and compared. The trends of these three BEM methods are nearly the same as the data generated by the software. However, there are small differences among these results. The BEM method without correction has more errors when the wind speed is low. The results by BEM method with corrections are more reasonable since it considers the real situation since classic BEM method is not suitable for the high value of the axial induction factor. The BEM method with Shen's correction has least difference with the QBlade data under various wind speeds among these three methods. Therefore, the BEM method with Shen's correction is more appropriate for

analysing the performance of wind turbine blades, which can be used for future work such as finite element analysis and maintenance strategies.

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