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Wind turbine blade damage aerodynamic profile analysis and its repair techniques

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Abstract

With the rapid maintenance cost increase of wind turbine blades, aerodynamic repairing principle can be a supplement to the structural repairing principle, which not only protects the blades from structural damage, but also meets the requirement of power generation efficiency. In this paper, the two-dimensional multi-scale flow field analysis method was employed to investigate the aerodynamic performance of the wind turbine blades damage and its corresponding repair techniques. Repairing principle for airfoil defects on the outer surface of the blade are given according to the blade's extended position. Firstly, the aerodynamic profile maintenance theory of wind turbine blades is introduced. Then, numerical simulation is performed for the pressure surface and suction surface of 45.3 shape blade damage. Corresponding repair principles are presented. Further, the generality of aerodynamic repairing principle is verified by the numerical simulation on 56.5 shape blade. Finally, the relevant case of Haiyuan Wind Power Station in Ningxia shows that the proposed aerodynamic repairing principle can effectively improve the power generation efficiency in practice.

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Keywords: Blade design; Aerodynamic profile; Numerical simulation; Aerodynamics; Repairing principle

1. Introduction

With the world's ever-growing energy consumption, environmental degradation and the depletion of fossil fuel sources are becoming more seriously. And there is an urgent need to develop renewable and clean energy sources. In the meantime, wind energy has gained considerable attention as a type of enduring, abundant and predictable renewable energy source [1,2]. The blades are generally regarded as the key component of wind turbine system, while the blade manufacture and repair technology are considered as the core of wind power generation. With the rapid capacity expansion of wind power generation, the majority of installed wind turbines are aging. However, the repair cost of wind turbine blades is so expensive that makes up 20–25% of total average cost produced over the

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lifetime. Thus, the improvement of maintenance and repair technology is a very important task for the development of renewable energy [3].

The repair techniques of wind turbine blades have been relatively matured in recent years. Some researchers paid attention to the repair materials of wind turbine blades [4–6]. A wind turbine blade is mainly a composite structure with epoxy resin as the matrix and glass fiber or carbon fiber as the reinforcement phase [7]. It has excellent characteristics such as light weight and high strength, as well as structural characteristics such as heterogeneity and anisotropy [8,9]. The current research status of crack damage for FRC wind turbine blade is comprehensively summarized from the formation mechanism of crack, the detection, and evaluation methods as well as the repair technologies [10]. Nowadays, more researchers focused on the monitoring techniques of blades in order to have effective maintenance plans for various losses [11,12]. Typical causes and types of blade damage that deserve to be considered during the running time are presented in [13]. Two different methodologies were successfully implemented to recognize deviating patterns from the healthy state, to detect anomalies in the dynamic response of wind turbine blades [14]. Predictive Analytics techniques in wind was used to optimize the operational life cost and the reliability of wind turbine blades in [15]. Besides, A short overview of main repair techniques for wind turbine blades and the related problems of computational mechanics was presented in [16]. A novel method for condition monitoring of wind turbine blades is proposed based on self-supervised learning [17]. Sudarsan Sahoo, et al. diagnose the faults in a wind turbine blade using vibration signals as the measured signal which is acquired from the hardware setup and classify the faults using different machine learning techniques and then the performance of the classifiers is compared [18].

However, the researches of repair techniques for wind turbine blades above hardly consider the effect of new local aerodynamic profile for blades. After nearly a hundred years of development, the study of wind turbine blades' aerodynamic profile has been relatively mature [19,20]. The wind turbine blades should be designed aerodynamically which results in complex geometry, and this issue can be solved using additive manufacturing [21]. A reasonable and efficient repair method based on the optimization design of ORLs is proposed in [22] to solve the lack of data foundation in the repair design of OWT blades, aiming at considering the efforts on both the structural strength and the aerodynamic performance. Rodolfo C.P. present an optimal design methodology which can be applied to turbine blades considering smooth and rough blade surface [23]. But how the local changes of aerodynamic configuration, the deviation of the manufactured blades and the designed aerodynamic shape, lead to the changes of conversion efficiency is still an issue that needs to be solved. The complex stress states of the blade are mainly caused by the aerodynamic loads generated by corrected blade element momentum theory, gravity loads, and centrifugal loads [24]. Hence, optimizing the aerodynamic performance of the wind turbine blades should be included into the repairing principle. It is only mentioned in the international standard for WT blade that the repair should consider the impact on aerodynamic characteristics, but there is no specific guidance basis [25]. According to the analysis and comparison between the numerical simulation and actual measured data, the local variation of aerodynamic profile in different regions of blades will enrich the existing structural repairing principle [26]. Then, the blades repair using revised repairing principle will effectively reduce the probability of secondary repair caused by unreasonable aerodynamic profile of blades. The combination of aerodynamic profile repair and structural repairing principles have more practical prospects.

In this paper, new repairing principle, for airfoil defects on the outer surface of the blade are given from the two-dimensional multi-scale flow field analysis of 45.3 shape blade with stress force and power efficiency as two repair indicators. The generality of repairing principles is verified by the simulation on 56.5 shape blade. Finally, the validity and feasibility of aerodynamic repairing principle are verified by the case of Haiyuan Wind Power Station in Ningxia.

2. Repair principle of the aerodynamic profile of wind turbine blade

2.1. Modified strip theory

The main theoretical basis for analyzing the aerodynamic performance of the blades in this paper is the modified strip theory. This theory is also called modified Momentum-Blade Element theory, which includes Betz theory, momentum theory, blade element theory, vortex theory and the tip and hub loss factor revised theory. The core is to analyze and design related aerodynamic profile based on the axial and circumferential induction factors.

Derived from the momentum theory and the blade element theory, the axial thrust and shaft torque equations of micro-segment dr, which is called blade element, are as follows:

$$\mathrm{d}T = 4\pi\rho V_0^2 a(1-a)r\mathrm{d}r = (1/2)\rho BcV_{rel}^2 C_N \mathrm{d}r \tag{1}$$

$$\mathrm{d}M = 4\pi\rho\Omega V_0 b(1-a)r^3\mathrm{d}r = (1/2)\rho BcV_{rel}^2 C_T \mathrm{d}r \tag{2}$$

where r is a radial position of blade's radius, T is the axial thrust, M is the shaft torque, ρ is the air density, V_0 is the velocity of wind flow in front of blade, Ω is the rotational angular velocity of blade, B is the blade number, c is the chord length of airfoil, V_{rel} is the synthetic relative wind velocity at blade element dr. a is the axial induction factor that is defined as $a = V_a/V_{0,}$ while b is the circumferential induction factor that is defined as $b = \omega/2\Omega$, in which V_a represents the axial induction velocity at blade element dr and ω represents the tangential induction angular velocity at blade element dr. C_N and C_T represent the normal force coefficient and the tangential force coefficient respectively. And the blade's radius is expressed by R. Supposing that the rotor solidity σ is defined as:

$$\sigma = Bc/2\pi r \tag{3}$$

The formulas about axial thrust and torsional moment obtained by the momentum theory combined with blade element theory are as follows:

$$a/(1-a) = \sigma C_N/4\sin^2\phi \tag{4}$$

$$b/(1+b) = \sigma C_T/4\sin\phi\cos\phi \tag{5}$$

where ϕ is the velocity angle of the inlet air at blade element dr.

The axial induction factor a and circumferential induction factor b can be derived by iteration of the equations above. Then, the axial thrust and shaft torque will be obtained. However, the simple strip theory does not consider the radial flow of airflow along the blade tip and root, which greatly affects the whole performance of the wind turbine. The tip loss correction factor F is introduced as:

$$F = (2/\pi)\arccos(\exp(B(r-R)/2r\sin\phi)) \tag{6}$$

However, the analysis of equations above ignores that the number of actual wind turbine blades is limited. Thus, based on the amendment of *Wilson* and *Lissaman* [27], *de Vries* proposed another correction model to amend the mass and flow again. Then, a correction factor f_1 is introduced to modify the normal force coefficient C_N and tangential force coefficient C_T as:

$$f_1 = (2/\pi)\arccos(exp(gB(r-R)/2r\sin\Phi)) \tag{7}$$

where $g = \exp(-0.125(B\lambda - 21)) + 0.1$, and $\lambda = \Omega\mathrm{R}/V_0$. Thus

$$C_{N\ \mathrm{modified}} = f_1 C_N \tag{8}$$

$$C_{T\ \mathrm{modified}} = f_1 C_T \tag{9}$$

Finally, considering the orthogonality between induced velocity and free stream velocity, and the modified C_N and C_T, the equations about blade's axial and circumferential induction factors are modified as:

$$(1-aF)aF/(1-a)^2 = \sigma C_N f_1/4\sin^2\Phi \tag{10}$$

$$bF(1-aF)/(1+b)(1-a) = \sigma C_T f_1/4\sin\Phi\cos\Phi \tag{11}$$

2.2. The repairing principle of wind turbine blades

In general, practical repair guidelines mainly include that:

- The interlayer displacement of staggered floor reaches to more than 50 mm.
- The same interlayer must use the same type of fiberglass-cloth.
- The lap of same interlayer should be more than 50 mm.

However, structural repairing principle ignores the impact of new structure on power generation efficiency. So, aerodynamic repairing principle, a supplement to the structural repairing principle, can avoid the secondary repair problem caused by the obvious reduction of the power generation efficiency under structural repairing principle. In this condition, they are consequently converted to practical repair guidelines, which mainly include that:

- The interlayer displacement of staggered floor reach to more than 100 mm.
- Smoothing repair is required for the defects.
- Modification shape repair for the airfoil.

In general, there are about 18 kinds of airfoil defect for blades' outer surface, includes delamination driven by a tension or buckling load, the damage caused by transport, storage, assembly, the oversize of airfoil profile, and so on. According to the position of the defects on the airfoil, they can be summarized into five categories: suction surface skin damage, pressure surface skin damage, oversize of trailing edge thickness, leading the edge and trailing edge damage.

In this paper, repairing principles for airfoil defects on the outer surface of blades are given according to Fig. 1. The corresponding classification is shown in Table 1. In Fig. 1, multi-scale model indicates that the scale of wind turbine blade-substructure is 1 mm–2 mm, and the scale of blade is 1–80 m. As seen in Table 1, the oversize of trailing edge thickness at area of blade's root will not result in structural problem, this kind of damage can be ignored. Since the leading-edge profile damage will produce stress concentration points, it is necessary to carry out the structural repair. When the airflow passes through the cylindrical section of the blade root, there basically has no speed change, which leads to almost the same stress in all areas of the blade. Due to the blade tip turbulence, the stress generated by the rotating airflow makes the airflow basically adhere to the blade's outer surface, which leads to the stress balance in this area and no longer provides lift. On the contrary, the stress distribution of ellipse transition area is uniform, which is the effective area contributing to the conversion of wind energy, so the repair

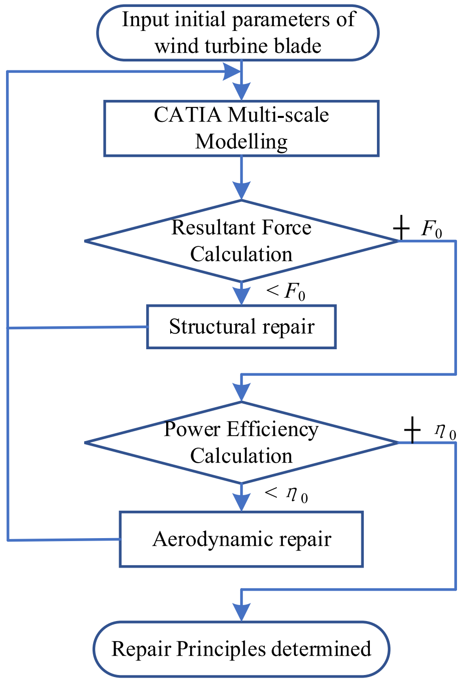


Fig. 1. Blade repair principles determination procedure.

Table 1. Classification of repairing principles.

Location	Damage of suction surface	Damage of pressure surface	Trailing edge thickness oversize	Damage of leading edge	Damage of trailing edge
Blade root area	Structural repair	Structural repair	Repair not required	Repair not required	Repair not required
Ellipse transition area	Structural repair	Structural repair	Repair not required	Repair not required	Repair not required
NACA63 airfoil area	Aerodynamic repair	Aerodynamic repair	Structural repair	Aerodynamic repair	Aerodynamic repair
Blade tip area	Structural repair	Structural repair	Structural repair	Structural repair	Structural repair

should primarily consider aerodynamic repair. Therefore, in NACA63 airfoil region, aerodynamic repairing principle should be used to the above 5 damages in Table 1 except for the damage of trailing edge thickness oversize.

3. Numerical simulation on the damage and repair of NACA63 airfoil section

3.1. Numerical simulation on the 45.3 shape blade's airfoil

In this paper, the software FLUENT is used to analyze and calculate the two-dimensional flow field. This paper takes the defect of pressure surface (PS) of NACA63 airfoil section as an example to analyze. And the relevant parameters of 45.3 shape blade are shown in Table 2.

Table 2. Parameters of the 45.3 shape blade.

Operation parameters	Value	Characteristic parameters	Value
Rated power	1.5 MW	Theoretic mass moment (From root)	112 480 ± 6% kg m
Rated speed	16.18 r/min	Total length	45 300 ± 25 mm
Super rotating speed	18.36 r/min	Maximum chord length	3183 mm
Rated wind speed	9.5 m/s	Deviation of length	±25 mm
Cut-in wind speed	3 m/s	Theoretic net weight of a blade	7100 ± 3% kg
Cut-out wind speed (Mean value in 10 min)	20 m/s	Theoretic gross weight of a blade (Include bolt, bolt sleeve, flange)	7575 ± 3% kg
Cut-out wind speed (Mean value in 3 s)	23 m/s	Barycenter of gross weight (From root)	14.9 ± 3% m
Extreme wind speed (Instantaneous in 3 s)	52.5 m/s	Barycenter of net weight (From root)	15.8 ± 3% m

The damage conditions and repair methods on pressure surface are as follows:

- Defect states of pressure surface: the depth of damage is 3–5 mm, and the length is 50 mm.
- Structural repair of pressure surface: the edge of the repair area is 3–5 mm higher than the surface of blade, the center area has a depression, and the repair length exceeds 50 mm at both ends of defect area.
- Aerodynamic repair of pressure surface: the edge of the repair area is 1–3 mm above the surface of blade, and the central area is filled with fiberglass to ensure the smooth transition of outer surface. The repair length exceeds 100 mm at both ends of defect area.

Under the states of PS defect and repair, the stress nephogram and velocity nephogram of 45.3 shape blade's NACA63 airfoil are shown in Fig. 2. It can be seen from Fig. 2(a) and (b) that, the stress state of damaged pressure

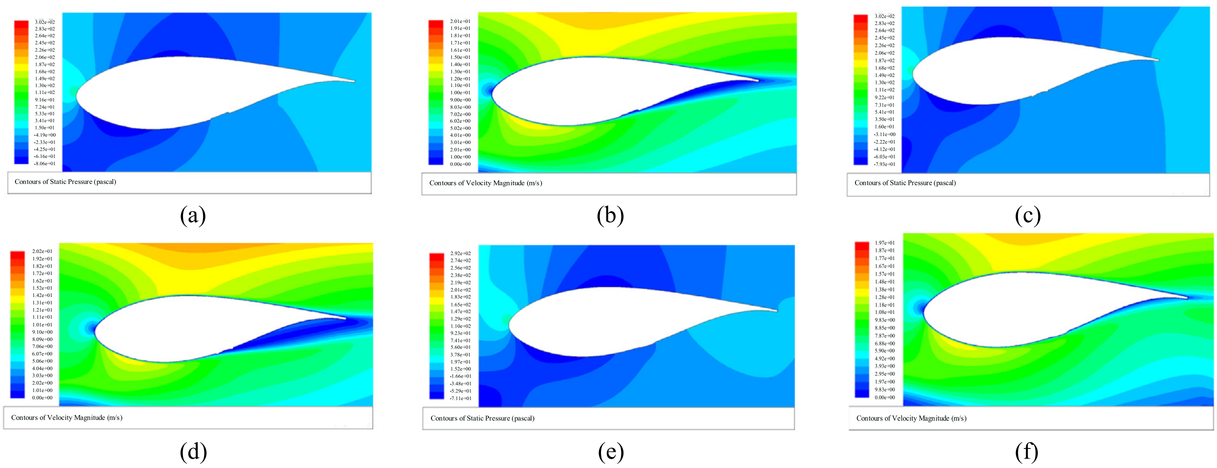


Fig. 2. Nephogram of the 45.3 shape blades' NACA63 airfoil. (a) stress nephogram of damaged PS; (b) velocity nephogram of damaged PS; (c) stress nephogram with structural repair; (d) velocity nephogram with structural repair; (e) stress nephogram with aerodynamic repair; (f) velocity nephogram with aerodynamic repair.

surface for 45.3 shape blade's NACA63 airfoil section changes obviously while the defect of pressure surface occurs. And stress interface moves to the edge of defect obviously. These phenomena indicate that stress concentration has occurred at the edge of defect. Consequently, it can cause the skin to be damage and fall off extensively. The calculated resultant force is 8.16 N, while the theoretical value is 23.50 N, which indicates that the power generation efficiency is only 35%. So, this defect should be repaired whether in structural or aerodynamic repairing principles.

As can be seen from Fig. 2(c), the damaged pressure surface's stress state of 45.3 shape blade's NACA63 airfoil section after structural repair is nearly consistent with the undamaged state. And each point of entire repairing area is in the same stress interface. However, from Fig. 2(d), it can be found that there is a large area of stalling space from the repairing area of blade. The stalling space caused by the blade surface roughness will influence the airflow velocity of blade's surface and the power of rotating blade. And then result in a decline of power generation efficiency [23]. The calculated resultant force is 13.32 N and the power generation efficiency is about 57%. Thus, it cannot meet the operation requirements. From Fig. 2(e) and (f), it can be seen that under the guidance of aerodynamic repairing principle, the stress state and gas flow velocity are basically stable. The calculated resultant force is 18.84 N and the power generation efficiency reaches to 80%, which meet the normal operation requirements.

3.2. Numerical simulation on the 56.5 shape blade's airfoil

Corresponding numerical simulation on the damage and repair of 56.5 shape blade's airfoil was carried out.

Relevant parameters of 56.5 shape blade's airfoil are shown in Table 3. In order to confirm the universality of aerodynamic repairing principle, 30 m airfoil section of pressure surface damage was chosen to analyze the related aerodynamic performance.

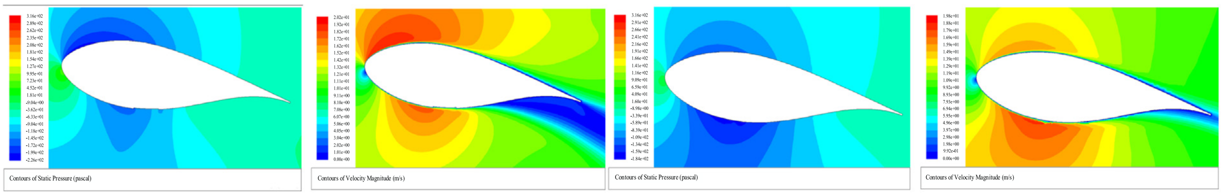
Table 3. Parameters of the 56.5 shape blade.

Operation parameters	Value	Characteristic parameters	Value
Rated power	2.2 MW	Theoretic mass moment (From root)	234 540 ± 3% kgm
Rated speed	14.4 r/min	Total length	56 500 ± 50 mm
Super rotating speed	15.84 r/min	Maximum chord length	3980 mm
Rated wind speed	9.3 m/s	Deviation of length	±50 mm
Cut-in wind speed	3 m/s	Theoretic net weight of a blade	12 890 ± 3% kg
Cut-out wind speed (Mean value in 10 min)	20 m/s	Theoretic gross weight of a blade (Include bolt, bolt sleeve, flange)	13 420 ± 3% kg
Cut-out wind speed (Mean value in 3 s)	25 m/s	Barycenter of gross weight (From root)	17.3 ± 3% m
Extreme wind speed (Instantaneous in 3 s)	37.5 m/s	Barycenter of net weight (From root)	16.7 ± 3% m

The damage conditions and repair methods on pressure surface are as follows:

- Damage conditions of pressure surface: the damage area is the central area of pressure surface, the width of damage is 200 mm, the depth is 5 mm and the length is 20–40 mm.
- Aerodynamic repair of pressure surface: the width of repairing area is 200 mm, the length is 36 m–40 m, the height is 3 mm, and staggered floor of both sides are 100 mm.

Under the states of PS damage and aerodynamic repair, the stress nephogram and velocity nephogram of 56.5 shape blade's NACA63 airfoil are shown in Fig. 3.



(a) (b) (c) (d)

Fig. 3. Nephogram of the 56.5 shape blades' NACA63 airfoil. (a) stress nephogram of damaged PS; (b) velocity nephogram of damaged PS; (c) stress nephogram with aerodynamic repair; (d) velocity nephogram with aerodynamic repair.

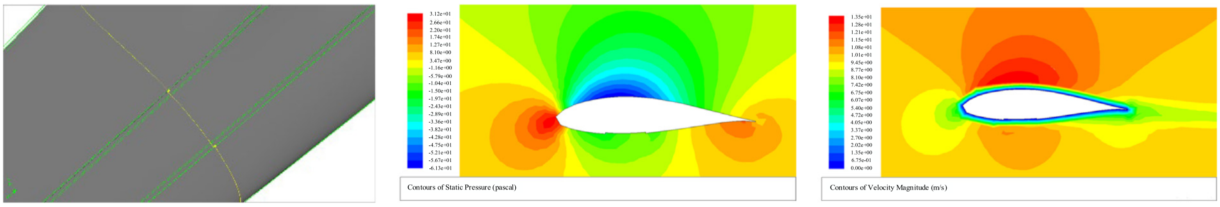
From Fig. 3(a), it is obvious that there is a typical phenomenon called stress concentration at the edge of pressure surface. This force condition will lead to massive structural damage of the wind turbine blades like stripping of skin in a large area. The other parts of airfoil cross section, smooth and uniform distribution in figure, is basically the same as that of the stress nephogram of damaged 45.3 shape blade's pressure surface. Fig. 3(b) shows that the airfoil cross section near the trailing edge has a wide range of stalling space from pressure surface damage area. The normal velocity, calculating gradient to the edge of damage area, will drop with expedition, which will seriously reduce the power generation efficiency. The simulated power derived directly by using the "Report/Forces" command in FLUENT is 1 364 258 W, while the design requirement is 2.2 MW. It is only about 62% of theoretical value.

From Fig. 3(c), it is obvious that the stress distribution tends to be uniform after repair. Fig. 3(d) shows that the gas flow velocity is well distributed and the gradient of speed varies identically after aerodynamic repair of pressure surface. The large-area stalling space in the trailing edge of pressure surface disappears. So, the power conversion efficiency will not reduce significantly and meet the requirements.

4. Experimental results

In 2013, the annual generating capacity of one of the wind turbines in Haiyuan Wind Power Station in Ningxia was significantly lower than those of the other units. However, the repaired units were basically the same as the remaining units in the statistics of annual power generation in 2015 and 2016.

In this paper, three blades were all set to pressure surface damage. Setting parameters of pressure surface damage conditions: the damage width is 200 mm, the length is 36 m–40 m and the depth is 5 mm. The damaged airfoil, the stress nephogram and the velocity nephogram at 37 m are shown in Fig. 4.



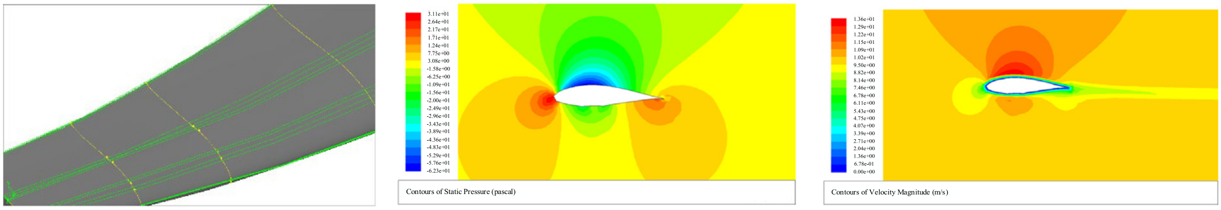
(a) (b) (c)

Fig. 4. (a) diagram of PS damage; (b) stress nephogram of PS damage; (c) velocity nephogram of PS damage.

From Fig. 4(b), it can be seen that the stress state of this section has changed obviously. And the stress interface moves to the edge of defect. The stress concentrated phenomenon in the edge of damage will lead to the further expansion of defect region, that is, large-scale falling off of surface skin. From Fig. 4(c), the damaged area leads to a wide range of stalling space from the damaged pressure surface, which means that this area has lost its function of generating power. Compared to the actual measurement value (1.1 MW), the simulated output power of wind turbine blade is 1.0 MW. The deviation comes from that remaining good blade. And the actual output power of blade should be 1.5 MW if there is no damage. If the effect of intact leaves is ruled out, the basic output power is only 0.3 MW compared to the rated power (0.5 MW). The power generation efficiency is only 60% of the theoretical value. It cannot meet requirements not only in structure but also in generating power efficiency.

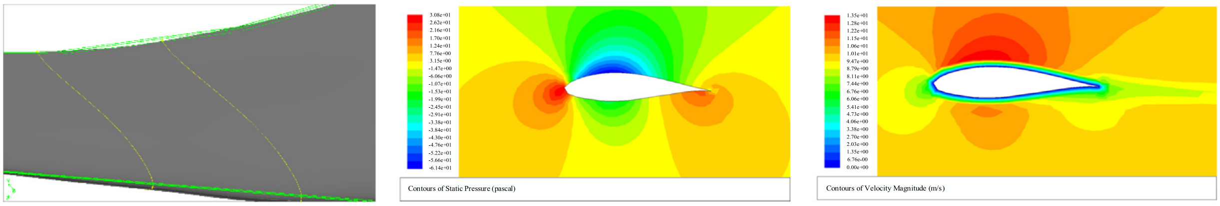
Then, the pressure surface damage of outer surface defects was repaired under the structural repairing principle. Structural repair diagram of wind turbine blades' airfoil, the stress nephogram and the velocity nephogram at 37 m are shown in Fig. 5.

It can be seen from the stress nephogram in Fig. 5 that except for seldom catastrophe points, the stress state of 45.3 shape blade is well balanced after structural repair. The velocity nephogram shows that there is still a wide range of stalling space after the structural repair. The output power of wind turbine blade is 1.2 MW, which is close to the actual measurement value (1.3 MW). If the effect of intact leaves is ruled out, the basic output power of a single blade is about 0.4 MW. Compared to the rated power, the power generation efficiency reaches to 80% of the theoretical value. We can see that after structural repair, this damage can meet the requirement of structure, but aerodynamic repair can be used to further improve generating power efficiency.



(a) (b) (c)

Fig. 5. (a) diagram with structural repair; (b) stress nephogram with structural repair; (c) velocity nephogram with structural repair.



(a) (b) (c)

Fig. 6. (a) diagram with aerodynamic repair; (b) stress nephogram with aerodynamic repair; (c) velocity nephogram with aerodynamic repair.

Next, the pressure surface damage of outer surface defects was repaired under the aerodynamic repairing principle. Aerodynamic repair of wind turbine blade's airfoil is shown in Fig. 6. Also, the stress nephogram and velocity nephogram at 37 m are shown in Fig. 6. From the velocity nephogram, according to aerodynamic repairing principle, the repaired airfoil profile shows a smooth streamline shape, which is close to the original NACA63 airfoil. The simulated output power of wind turbine blade is 1.4 MW, which is consistent with the actual measurement value (1.4 MW). The basic output power of a single blade is about 0.47 MW. And the power generation efficiency reaches to 94% of the theoretical value.

In addition, we also perform the leading edge profile (LEP) damage repair to verify the correctness of the proposed method. Set parameters of leading edge profile (LEP) damage conditions as: the damage width is 100 mm, the length is 20 m and the leading edge profile error is ±5 mm. And the damaged airfoil, the stress nephogram and the velocity nephogram at 37 m are obtained in Fig. 7. From Fig. 7, it can be found that the stress nephogram and velocity nephogram distribution become more even with aerodynamic repair too.

5. Conclusions

In this paper, repairing principle for airfoil defects on the outer surface of blades are given according to the blade's extended position. The ellipse transition area of the wind turbine blade, using the structural repairing principle, can only protect blades from structural damage rather than meet the requirement of power generation efficiency. At the same time, aerodynamic repairing principle becomes a supplement to the structural repairing principle. According to the measured data analysis, the numerical model of wind blade damage and repair state is determined. Applicable areas and basic requirements for deriving principles of aerodynamic rehabilitation are derived. From numerical simulation and experiment, it can be seen that under the structural repairing principle, the stalling space caused by the blade surface roughness will result in a decline of power generation efficiency. After the aerodynamic repairing principle, the power generation efficiency has been improved by about 20%. On the one hand, the aerodynamic repairing principle can effectively solve the secondary repair problem caused by the decline of power generation efficiency after structural repair. On the other hand, it can deal with some damages that do not need structural repair but cannot meet the requirements of power generation efficiency. Especially, it is more suitable for the repair of the blade critical areas, especially for the damaged NACA63 airfoils.

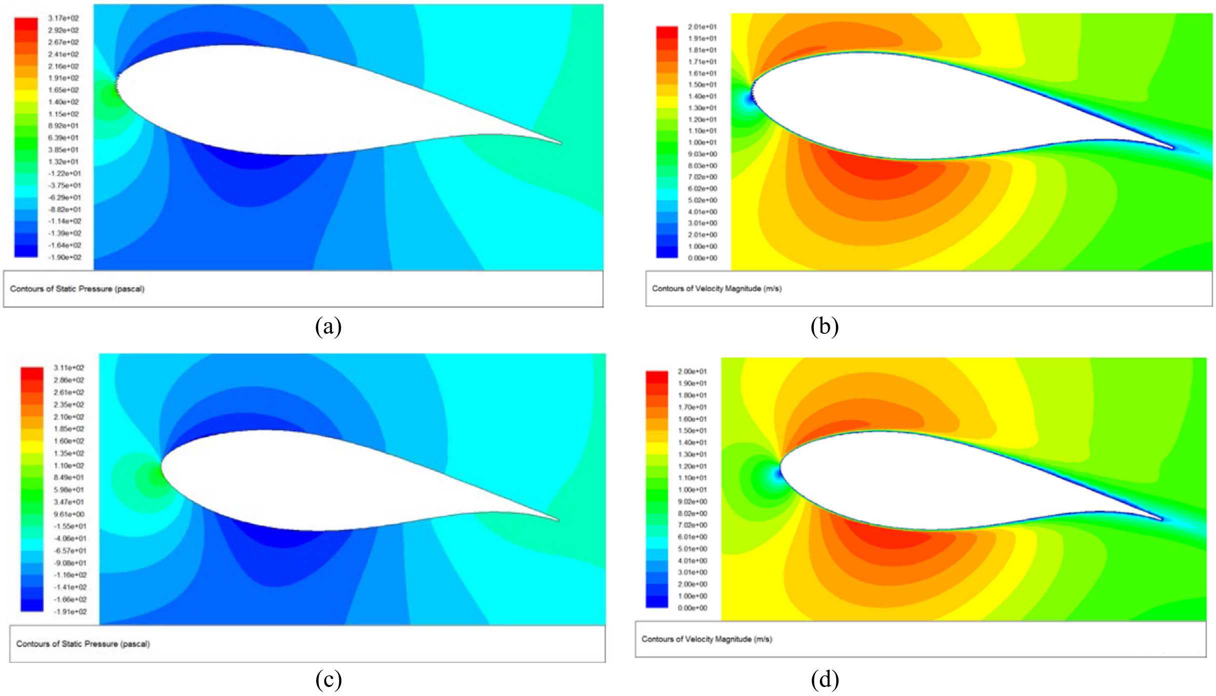


Fig. 7. (a) stress nephogram of LEP damage; (b) velocity nephogram of LEP damage; (c) stress nephogram with aerodynamic repair; (d) velocity nephogram with aerodynamic repair.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hongwei Fang reports financial support was provided by National Natural Science Foundation of China. Hongwei Fang reports financial support was provided by Tianjin Municipal Natural Science Foundation.

Data availability

The authors do not have permission to share data

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