

## Independent research and development progress in large-scale wind turbine blade with coordinated aerodynamics, structure, and load\*

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**Abstract** According to the three key elements in blade design process, i.e., aerodynamic design, structure design, and load prediction, the independent research and development (R&D) progress of blade design is summarized and analyzed. The computational fluid dynamics (CFD) method, the vortex method, and the blade element momentum method (BEM) are described. Based on the widely used BEM method, the solutions for the blade design in low-speed wind area are obtained. A brief overview of the traditional design and analysis methods based on beam models is given. The defects of these methods used for simulating the structure of large-scale composite blade are analyzed. The application progress of the finite element method (FEM) used in the blade structure analysis is shown. The effects of load prediction on the blades and entire wind turbine are introduced. The progress in load forecasting is described. With the analysis of the relationship among these three key elements, it is concluded that developing a blade optimization design system with coordinated aerodynamics, structure, and load will truly meet the requirement of high efficiency and low cost. The main directions for further study are pointed out, e.g., high efficiency and low load airfoils, structural nonlinear finite element analysis, aerodynamic structure coupling research, and establishing different design standards. The aim is to establish a blade R&D system suitable for the conditions of wind resources in China and promote the development of wind power in the country.

**Key words** wind turbine blade, aerodynamic design, structure design, load prediction

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### 1 Introduction

In recent years, with the rapid development of wind power industry in China, the installed capacity of wind turbine has been ranked first in the world. Now, wind power has exceeded nuclear power, and become the third largest source of power generation after thermal power and hydropower. At present, whether wind turbine development or blade design still mainly depends

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on foreign technology. However, the wind resource characteristics in China, i.e., low wind speed in the central area, big sandstorm in the northern area, and lots of typhoons in coastal area, are different from any foreign country, while foreign technology shows a “acclimatized” situation. To ensure the healthy development of Chinese wind power industry, it is necessary to study the native independent research and development (R&D) capabilities. Blade is the key component for converting wind energy to mechanical energy. Therefore, the independent R&D ability in blade design is important for the growth of wind power industry.

Blade design involves many aspects, e.g., aerodynamic design, structure design, and load prediction. It is a systematic project. Aerodynamic design, which is the basis for blade design, aims to seek the blade aerodynamic shape satisfying the aerodynamic performance design requirements, i.e., the maximum power coefficient and annual energy production. It has a direct effect on the structure design and load prediction. Structure design, which is a guarantee of blade reliable operation, aims to obtain the structure and ply forms meeting the requirement of strength, stiffness, and life under the conditions of the specific aerodynamic profiles. It determines the costs, and affects other links in the blade design. Load prediction aims to analyze and evaluate the extreme load and fatigue load under all operating conditions. Its accuracy and efficiency will have an important effect on the blade design. The accuracy will not only determine the property of the blade safety and service life, but also affect the structure design of other parts of the wind turbine. Moreover, the efficiency will directly affect the cycle of the blade design, especially for establishing an optimization design system with coordinated aerodynamics, structure, and load.

As can be seen, aerodynamic design, structure design, and load prediction are three key links for blade design. The following content will outline the research status and progress, combined with the corresponding research achievements from the research team of Institute of Engineering Thermal physics, Chinese Academy of Sciences.

## 2 Aerodynamic design

Aerodynamic design aims to obtain the best geometry profile meeting the aerodynamic design requirements, i.e., the maximum power coefficient and annual energy production, by changing the aerodynamic shape parameters such as the positions of the airfoil, chord, and twist.

### 2.1 Blade airfoil selection

Wind turbine blade airfoils evolve from aviation airfoils. Before the 1990s, wind turbine blade airfoils were generally designed by traditional aviation airfoils, e.g., NACA63 and NACA64 airfoils. These airfoils have a high ratio of lift to drag, and their aerodynamic data have been widely proved to be reliable. However, the existing traditional aviation airfoils cannot meet the following performance requirements:

- (i) To ensure the cross-sectional stiffness and geometric compatibility of the blade near the root, the blade needs airfoils with more than 30% relative thickness.
- (ii) The blade surface becomes rough when it is contaminated and eroded by dust, insects, and raindrops. It requires airfoils with low roughness insensitivity. This is because that the roughness of the airfoil leading edge has an important effect on the airfoil aerodynamic performance.
- (iii) Random gust, typhoon, and other factors in atmosphere may cause blade airfoil working at the stall condition where the vibration of the blade aggravates and even generates the destructive load. Therefore, it requires the airfoils having gentle stall characteristics.
- (iv) The maximum lift-drag ratio of an airfoil has a significant effect on the wind energy conversion efficiency. To increase the utilization rate of the wind energy, it is necessary to develop a higher lift-drag ratio airfoil.

To satisfy the above features and requirements, since the late 1980s, some research groups

in European and the United States of America have been searching for wind turbine dedicated airfoils, and have made certain achievements, e.g., the FFA airfoils designed by Swedish Institute of Aeronautical, the DU airfoils designed by Netherlands Delft University, the Risø airfoils developed by Denmark Risø National Laboratory, and the S8 airfoils designed by the National Renewable Energy Laboratory (NREL) of the United States of America. Among them, the DU airfoils are the most widely used airfoils in wind power industry.

However, with the development of wind energy in low wind speed area and offshore wind energy, blade length is increasing, and the running Reynolds number of airfoil is getting bigger. It has reached more than 6 million at the outer span of a blade. The existing dedicated wind turbine airfoils were only designed based on lower Reynolds numbers, and the experimental Reynolds numbers are less than 2 million. Therefore, there is an urgent need to develop wind turbine dedicated airfoils with good aerodynamic properties with high Reynolds numbers. To improve the utilization efficiency of wind energy close to the blade root as much as possible, it needs to design airfoils with larger relative thickness. Therefore, CAS airfoil families were developed<sup>[1]</sup>, whose relative thickness ranges from 18% to 60%, and the design Reynolds number reached 3 million. Compared with the corresponding DU airfoils and NACA airfoils, CAS airfoils have larger lift coefficient, better roughness insensitivity, and more gentle stall characteristics. However, with in-depth study, the functional requirements of airfoils at different span locations are refined better and better. The airfoils at the outer blade should have higher lift-drag ratios and lower noise levels. The airfoils at the inner blade should have good structural properties and aerodynamic properties at high angles of attack. These propose more stringent requirements for developing new airfoils.

## 2.2 Blade aerodynamic analysis

After selecting the blade airfoils, how to calculate and analyze the blade aerodynamic performance is the key for the aerodynamic design. The calculational fluid dynamics (CFD) method, the vortex method, and the blade element momentum (BEM) method are currently the main used methods. Based on the Navier-Stokes equations, the CFD method can simulate high precision three-dimensional (3D) flow field structure detailedly around the blade by generating 3D meshes and entering the right boundary conditions. Therefore, this method can directly predict the aerodynamic performance of the blade. Its accuracy is also the highest one among the three mentioned methods. However, the 3D flow field around the blade is multi-scale (the scale of the blade length, the boundary layer on the blade surface, and the trailing vortex structure differs by five orders of magnitude), the wind is unsteady and highly turbulent, and the blade surface is irregular. All of these features make the solution of the 3D flow field very complicated and time-consuming. Therefore, the application of the CFD method in engineering design is restricted. Now, the CFD method is mainly applied in the following two aspects in the field of wind power: (i) the analysis and optimization design of airfoils<sup>[2-3]</sup>; (ii) the calculation of the operation conditions under steady flow<sup>[4-6]</sup>. Sometimes, it also uses yaw, tower shadow effect, aerodynamic noise, and aeroelastic coupling<sup>[7-8]</sup>. However, with the development of computer technology, it becomes more and more close to the engineering applications.

The core idea of the vortex method is to simplify the vorticity distribution in 3D flow field. It is working in conjunction with a rigid or free wake vortex model to calculate the blade aerodynamic performance. According to the simplified forms, the vortex method can be divided into a lift line model, a lifting surface, and a 3D surface element model. The lifting line and lifting surface model usually use the 3D Bio-Sarvart theory. To a certain extent, it improves the ability to analyze the 3D flow field<sup>[9]</sup>. However, its accuracy depends on the two-dimensional (2D) experimental lift and drag coefficients of the airfoil. Compared with the BEM method, its calculation time is longer. All these limit its applications in the engineering design. The 3D surface element model changes the linear partial differential equations into the form of domain boundary integral. Then, the 3D potential flow field is calculated by the geometric grid and trailing vortex grid attached to the blade surface. This method does

not need 2D experimental lift and drag coefficients of the airfoil. Therefore, it has higher precision. Compared with the CFD method, the number of the grids is greatly reduced, and the calculation efficiency of the 3D flow field is improved<sup>[10]</sup>. Therefore, it is an important direction for the future research to calculate the aerodynamic performance of the blade. The 3D surface element method was first introduced by Hess and Smith<sup>[11–12]</sup> for calculating the flow around the non-lifting body and the lifting body. Since then, Newman<sup>[13]</sup> derived the geometric calculation method for the influence coefficient, which laid the foundation for the widely used surface element model. However, since the 3D surface element model is based on the assumption of potential flow, the application is limited in viscous flow and large separate flow. For this purpose, our research team combined the 3D surface element model with the boundary layer model, and established a viscous inviscid coupling model<sup>[14]</sup> based on the direct coupling mode, which could be used to analyze the NREL phase VI wind turbine. The results showed that the introduction of the boundary layer thickness not only improved the accuracy of the 3D surface element model but also expanded the ability of the viscosity calculation. Moreover, our research team first proposed the PANROM coupling model in conjunction with the reduced-order model (ROM) and the surface element model<sup>[15]</sup>, which greatly improved the accuracy at large flow separation. Certainly, applying this method to the actual blade design needs to further reduce the calculation time and improve the accuracy at large flow separation.

The BEM method is based on the theory of one-dimensional (1D) momentum and 2D blade element. It uses 2D experimental lift and drag coefficients of the airfoil, and calculates the blade aerodynamic performance by introducing the axial and tangential induce factor. Since meshing the flow field is not needed, the calculation time is shortened (calculating the blade performance only needs a few seconds). Moreover, the blade is divided into many blade elements independently, which is easily for the integration with the structural dynamics model of the blade. Therefore, it is the most widely used method in the engineering design at present. It is also used by the current wind turbines dedicated the software GH Bladed and FOCUS. Of course, it greatly simplifies the actual rotor model, resulting in a big error in simulating the dynamic inflow, dynamic stall, 3D flow field characteristics and so on. Therefore, to improve the accuracy of this method, some correction models combining the theoretical analysis with the empirical coefficients constantly put forward<sup>[16–18]</sup>, e.g., the Prandtl tip loss correction model, the Leishman-Beddoes dynamic stall model, and the 3D correction model. Our research team also developed an improved induce factor algorithm, and gained good effects<sup>[19]</sup>. However, these correction models contain empirical constants. Therefore, the versatility greatly reduces.

With the development of wind energy in low wind speed area in China, the blade root load has become an important constraint during the blade design. This is mainly because that, the blade length needs to be increased so as to capture more wind energy from a low wind speed, leading to an increase in the blade root load. To control it, our research team systematically analyzed the BEM method. Without considering the drag loss and tip loss, the optimal aerodynamic shape of the blade was gotten, and it satisfied the following equations<sup>[20]</sup>:

$$\sigma_r \lambda_r C_L = \frac{4\lambda^2 \mu^2 a'}{\sqrt{(1-a)^2 + (\lambda\mu(1+a'))^2}}, \quad (1)$$

$$a = \frac{1}{3}, \quad a' = \frac{a(1-a)}{\lambda^2 \mu^2} \quad (2)$$

where  $\sigma_r$  was the local solidity defined by  $\sigma_r = 3c/2\pi r$ ,  $\lambda_r$  was the local tip ratio defined by  $\lambda_r = \Omega r/V$ ,  $C_L$  was the lift coefficient at the design angle of attack,  $\lambda$  was the design tip speed ratio,  $\mu$  was the span ratio defined by  $\mu = r/R$ ,  $a$  was the axial induce factor, and  $a'$  was the tangential induce factor.

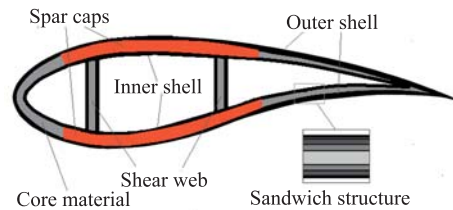
By simultaneously analyzing the impacts of different design parameters on the rotor power and the extreme loads at the blade root, the following conclusions are obtained<sup>[21]</sup>: Under the

same conditions of design angle of attack and wind turbine model, with an increase in the design tip speed ratio, the maximum power coefficient of the rotor was essentially invariant, the optimal tip speed ratio increased, while the flapwise bending moment and torsional moment at the root decreased. Based on these conclusions, we can see that the aerodynamic design with a high tip speed ratio is easier to meet the design requirements in low wind speed area. Since the design angle of attack is directly related to the blade airfoil, developing new wind turbine dedicated airfoils with high efficient and low load level is also an important solution for this constraint problem.

It can be also seen from Eq. (1) that, when the design angle of attack keeps the same and the design tip speed ratio increases, the blade chord decreases and the blade root load decreases along with the degradation of the structural performance of the blade, which will affect the blade structure design unfavorably. Therefore, designers need to find the best balance among aerodynamic design, structure design, and blade load in order to achieve the optimal blade design.

### 3 Structure design

The current large-scale wind turbine blade is mainly a shell structure made of composite materials. A typical blade section consists of spar cap, leading and trailing edge, shear web, and sandwich structure (see Fig. 1). Among them, the spar cap mainly bears the flapwise moment, the leading and trailing edge mainly bears the edgewise moment<sup>[22]</sup>, and the shear web is mainly against the transverse shear load and keeps the aerodynamic shape together with the sandwich structure under load. The aim of the structure design is to obtain the laminate parameters, e.g., the laminate thickness, the width, and the order, which meet the design requirements of stiffness, strength, and stability in the blade spar cap, the leading and trailing edge, the shear web, and the sandwich structures.



**Fig. 1** Structure of layers in blade section

Thus, it needs modal analysis, stiffness analysis, ultimate strength analysis, and fatigue analysis. Different analyses have different purposes. The modal analysis requires the blade natural frequencies to avoid the resonance range of the wind turbine, the stiffness analysis demands enough clearance between the blade tip and the tower surface, the ultimate strength analysis is intended to check whether the material and structure is reliable and stable under the extreme loads, and the fatigue analysis requires every blade material to be safe under the fatigue load in at least 20 years.

Generally, the initial structure design of blade is based on a 1D gradual beam model. The beam model uses the stiffness and mass distribution of a 2D cross-section of the blade as the input conditions. During the initial design, the structural plies of each section are parameterized. The structural properties of each section are then obtained by the classical laminated plate theory. According to the above results, using the beam theory, the blade natural frequencies and mode shapes are calculated, the overall deflection is analyzed, and the strength of every material is evaluated. This analysis method built on the beam model is fast and simple, and

easily combined with the optimization algorithm. Therefore, it is suitable for the preliminary design and optimization of the blade structure<sup>[22]</sup>.

However, the beam model ignores the details of the constructions and the connections in 3D composite layout. It is unable to calculate the instability of thin-walled plates and shells. Therefore, it cannot meet the requirements of the precise analysis about the blade structure. At present, in the structure check of the full-scale blade, the 3D finite element model has been widely used<sup>[23–26]</sup>. The finite element model using the shell element or solid element can analyze the structural details of the bolt connection, the structure adhesive bonding, and the stacking sequence. Since large-scale wind turbine blade has elongated cavity and thin shell structure, delamination and buckling are the main failure forms for the blade<sup>[27]</sup>. Therefore, detailed structure analysis and buckling stability analysis are important for checking large-scale wind turbine blade structure.

Our research team also used the beam model at the preliminary design and optimization and 3D finite element models to check the reliability. Through our research and full-scale failure test for the 52.3m wind turbine blade, some new results were found. First, the blade exhibited multiple failure modes. Among various observed failure modes, the delamination of the unidirectional laminates in the spar cap was identified to be the catastrophic failure of the blade. The through-thickness stresses could significantly affect the failure of the large composite blades<sup>[28]</sup>. Therefore, with the increase in the thickness of the blade layer, the thick laminate theory and 3D solid elements in the finite element models should be used. Besides, the failure damaged by typhoon were also studied<sup>[29–30]</sup>. It was found that the stop position was critical to the turbine failure, which is very useful for the design of offshore wind turbine.

## 4 Load prediction

### 4.1 Load calculation method

Wind turbine blade load is mainly the result of the coupling effect of aerodynamics and structure. Therefore, calculating the load involves a complex aeroelastic response process. The calculation method depends on the improvement and perfection of the aerodynamic, structural dynamic, and coupling iterative algorithm. Currently, the technique combining the BEM method with the modal analysis method in a weak coupling way is widely used in actual blade design. This is because that the calculation time is short and the accuracy meets the design requirements. The FLEX5 developed by Technical University of Denmark, the commercial software GH Bladed developed by Garrad Hassen in the United Kingdom, and the FAST developed by the NREL are using such technique. However, the models used in this method are simplified, which need to be improved in many respects. For the aerodynamic calculation, the BEM method cannot reflect the 3D flow field around the blade and the pressure distribution on the blade surface. It is necessary to adopt the CFD method to solve the aerodynamic performance. For the structural analysis, the blade is getting large-scale and more flexible, while the torsional frequency of the blade continuously reduces. It leads to the torsional mode coupling with a low order edgewise mode or flapwise mode. Therefore, the structure response is more complex. Ahlstrom<sup>[31]</sup> found that the elongated and flexible blade will have a greater flapwise deformation under the aerodynamic thrust, which might cause nonlinear coupling between the edgewise and the torsion. Moreover, modern large-scale blade has bending-torsion profiles. Therefore, the blade becomes a curved beam, and the coupled vibrations are more noticeable. To improve the calculation accuracy of the structural response, it needs to consider the torsion mode and geometrical bending property in the blade modal analysis. For this purpose, our research team divided the blade into many curved beam elements, re-derived the finite element shape function, and did coupling dynamic simulation. Regarding the experimental results, this model was accuracy<sup>[32]</sup>. Besides, the blade geometrical nonlinearity cannot be ignored in large-scale blade. But the modal analysis method is based on the assumption of small deformation. Therefore,

developing the blade geometrical nonlinear analysis method is important in improving the accuracy of the aeroelastic calculation. However, the coupling iteration algorithm is still based on a weak coupling manner. That is, the aerodynamic calculation and the structural response are done independently. Therefore, it cannot actually reflect the coupling behavior between the aerodynamic and the structure. At the same time, the way of load applied in the model during the structural response analysis cannot restore the actual load condition on the blade. These will result in the increase in the calculation error, which needs to be further studied.

Moreover, atmospheric turbulence has a significant impact on the blade load. In particular, some sudden and high turbulence intensity typhoon will increase the blade dynamic load greatly, or even cause damage to the blade. They are out of the scope of the IEC and GL standards. It must be specially analyzed. From the Reynolds-averaged Navier-Stokes equation, it can be seen that, the Reynolds stress represents the effects of the turbulent diffusion. In the wake of wind turbine, the Reynolds stress is much larger than the molecular diffusion viscous force. Therefore, atmospheric turbulence has an important role in the development of wind turbine wake. However, with the development of wind turbine wake, the blade load and power generation capacity of wind turbine will be seriously affected. Currently, the widely used turbulence model in the CFD method for calculating the flow field around the wind turbine is based on the RANS turbulence model and the large eddy simulation (LES) model. According to the methods for solving the Reynolds stress, the RANS turbulence model includes a linear eddy viscosity model, a nonlinear eddy viscosity model, and a Reynolds stress model (RSM). The linear eddy viscosity model includes an algebraic model, a one-equation model, and a two-equation model. Except the Reynolds stress model, most of the RANS turbulence models are based on the Boussinesq assumption. Studies have shown that the Boussinesq assumption is not possible to accurately represent the sudden change of the average strain rate and anisotropic turbulence in the flow field<sup>[33–34]</sup>. For the flow field around the wind turbine, the atmospheric turbulence has anisotropic characteristics, and the fluid average strain rate tends to be larger in the wake region, particularly in the near wake region. These factors can lead to errors in the simulation of flow field by use of the RANS turbulence model. In recent years, because large eddy simulation has advantages in unsteady flow, anisotropic turbulence, turbulent mixing and so on, it has been paid more and more attention to. Réthoré<sup>[35]</sup> used the RANS model ( $k$ - $\epsilon$ ) and the LES model to calculate the flow field in wind turbine wake, respectively, and compared the results of different turbulence models. The results showed that, the LES, whether the average velocity profile or wake turbulence, had greater advantages. But it costs several days calculation, while the RANS model needs only a few hours calculation. Hence, if this type of CFD calculational models is applied to practical engineering design, it needs much improvement in the calculational efficiency.

#### 4.2 Load prediction method

Load prediction mainly includes fatigue load prediction and extreme load prediction. Since blade loads are decided together by the wind conditions, aerodynamics, structure, materials, control parameters and so on and there are also strong non-linear relationships among some of them (such as the rotor speed, the pitch angle, and the wind speed), blade load prediction is very complex. Currently, the common assessment method is usually used to calculate and statistically analyze the load cases according to the IEC or GL standard to get the blade extreme and fatigue loads. However, this method not only is time-consuming but also cannot reflect the regularity of the parameters affecting the blade loads.

To reduce the calculating time while ensuring the accuracy, some new load evaluation models have been provided during the last decade. However, the corresponding research is still limited in China. Almost all of the existed extreme load evaluation models are established according to the calculation results from the finite load cases or measurement data, by which the statistical models and extrapolated models are used to get the extreme load within a longer time and a wider range<sup>[36–38]</sup>. Jensen et al.<sup>[38]</sup> used the first-order reliability method (FORM) and Monte

Carlo simulation (MCS) to predict the extreme load from wave and wind. Chen and Wang<sup>[39]</sup> used the statistical models to predict the blade root moments on the basis of summarizing the previous used model. However, these models have several common problems, which are difficult to solve, e.g., how to find a suitable probability distribution function for the known data, how to get the long-term load distribution from the short-term load distribution, and how to define the uncertainty of the predicting results. Some empirical formulas are developed for the fatigue load. Fuglsang and Madsen<sup>[40]</sup> used a semi-empirical gradient formula to assess the blade fatigue load. Kong et al.<sup>[41]</sup> used the empirical formula raised by Spera to evaluate the blade fatigue load. Although these assessment methods about fatigue load are simple, they cannot guarantee the accuracy. Moreover, the above load evaluation models cannot reflect the effects of various parameters on the load, and such effects are seldom studied. Moriarty et al.<sup>[42]</sup> studied the effects of the characteristic parameters of turbulent wind on the ultimate load. Thomsen and Sorensen<sup>[43]</sup> studied the effects of some parameters of the wind field on the fatigue load. Since there are many factors affecting the load, it is necessary to study the effects of other wind turbine factors on the load in depth, especially the key factors of the rotor speed and the pitch angle.

For this purpose, our research team did derivation and analysis about the effects of these factors. On this basis, a new extreme load prediction model was developed. In this model, the extreme load prediction was taken as an extreme value optimal problem<sup>[44]</sup>. The aerodynamic force  $F$  and moment  $M$  on the blade were defined by

$$(F, M) = f(\gamma, \chi, t, \beta_2, \Omega, \beta_1, c, V_1, \psi, \rho, C_L, C_d) \quad (3)$$

where  $\gamma$  was the yaw angle,  $\chi$  was the cone angle,  $t$  was the tilt angle,  $\beta_2$  was the pitch angle,  $\Omega$  was the rotor speed,  $\beta_1$  was the twist angle,  $c$  was the chord length,  $V_1$  was the wind speed (including magnitude and direction),  $\psi$  was the azimuth angle,  $\rho$  was the air density, and  $C_L$  and  $C_d$  were the lift and drag coefficients, respectively.

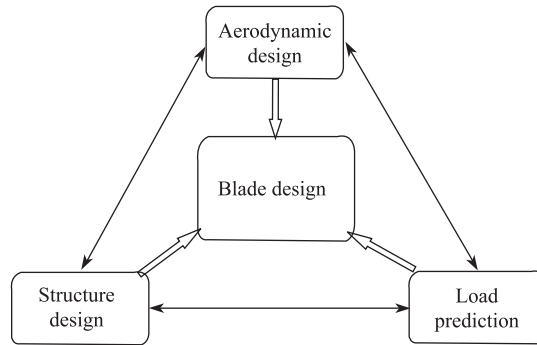
Then, on the basis of comprehensively analyzing the possible operating conditions, the range of each variable and the coupling relationships among the parameters were obtained. Finally, the improved particle swarm optimization (PSO) algorithm was used to solve the extreme load. The results by use of this model showed that it met the accuracy requirements of engineering design and its calculation time was greatly reduced. Certainly, its accuracy should be improved. Accurately, building the coupling relationships among the pitch angle, the rotor speed, and the wind speed still needed to be further studied.

## 5 large-scale wind turbine blade optimization design method with coordinated aerodynamic, structure, and load

Currently, large-scale wind turbine blade design method with coordinated aerodynamic, structure, and load has become a trend. This is mainly determined by the following two aspects. First, there are mutual influence and constraint relationships among different key links. As shown in Fig. 2, aerodynamic design affects the magnitude and distribution of the load, resulting in the effects on the structure design. Structure design not only affect the design load, but also has a restriction effect on the aerodynamic design. The load prediction bases on the known aerodynamic and structure design, while in turn limits the aerodynamic design and structure design. Second, blade design is a multi-parameter, multi-constraint, and multi-objective optimization process. The design parameters includes the chord length, the twist angle, the airfoil, the position, and the thickness distribution of the spar cap. The constraints include the tip deformation, the ultimate stress, the fatigue stress, and the frequency. The goals include the maximum annual energy capture, the maximum power coefficient, the minimum weight, and the minimum blade cost. There are strong non-linear relationships among the parameters, the constraints, and the objectives. Therefore, carrying out the corresponding



research will provide effective tools for designing more efficient and low cost blade and meet the needs of the technological progress of Chinese wind power industry.



**Fig. 2** Relationships of aspects in blade design

Due to the complexity of large-scale blade optimization design, only a few authors have established blade optimization design models. In the early research, blade optimization designs were focused on aerodynamics<sup>[45–47]</sup>, which were mainly about the question that how to arrange the aerodynamic shape of the blade so that the blade aerodynamic efficiency could be made higher. Along with the development of research, more and more studies shifted the focus from aerodynamics to structure reliability and economy<sup>[48–51]</sup>, where how to arrange the structure, the material location, and the material layup so as to make the structural characteristic better and weight lighter was the mainly considered, and the coupling influence between aerodynamics and structure was also taking into account.

Liao et al.<sup>[52]</sup> developed an optimized design method combining the particle swarm optimization algorithm with the FAST program to reduce the weight of a 1.5 MW wind turbine blade, and obtained good effectiveness. With the continuous development on the simplified load prediction model and the improved multi-objective optimization algorithm, it is expected to establish a leading large-scale blade optimization design method with coordinated aerodynamics, structure, and load. However, many issues need further to be studied and improved, e.g., how to consider the aerodynamic design goal, how to bring in the extreme load evaluation model, and how to assess the fatigue load.

## 6 Conclusions

In summary, the research team of Institute of Engineering Thermophysics, Chinese Academy of Sciences has extensively studied the research and development of large-scale wind turbine blade design systems. A large-scale wind turbine blade design method with coordinated aerodynamics, structure, and load is initially formed.

(i) The current engineering design method is still mainly based on the BEM model. In addition to the blade chord and twist angle, airfoil characteristics have an important effect on the design. Hence, it is necessary to research and develop new dedicated airfoils, such as blunt trailing edge airfoils and high efficient and low load airfoils, to obtain better aerodynamic design.

(ii) The finite element method has been widely used in structure design and analysis. When the blade becomes large and flexible, the effect of the geometric nonlinearity on the accuracy of the structural analysis cannot be ignored. At the same time, the nonlinear properties of the blade materials have a significant impact on the failure analysis of the blade. Therefore, carrying out a nonlinear finite element analysis is an inevitable requirement and research focus for large-scale blade design.

(iii) The blade load calculation is based on the aerodynamic-structure coupling analysis. The known aeroelastic coupling algorithms are built on the idea of weak coupling, which cannot actually reflect the aerodynamic-structure coupling process. Therefore, studying the theories and methods about the blade aerodynamic-structure coupling analysis in-depth and building high-precision aeroelastic analysis model are important research directions for the increase in the load prediction accuracy.

(iv) At present, load prediction is almost done by calculating the load cases specified in the IEC or GL standard. However, it cannot fully reflect our unique wind resource characteristics, which possibly cause the blade safety margin excessive or inadequate. Therefore, it is necessary to establish different design standards more suitable for the wind resource characteristics of our country and even different regions. It is also the inevitable requirement and important research content for the development of the wind power industry in China.

The ultimate aim of the above studies is to establish the blade R&D design system suitable for the wind resource characteristics in China, to promote the sustainable and healthy development of the wind power industry in China, and to improve its technological level and the international competitiveness.

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