Journal of Marine Science and Application (2025) 24: 120-136
https://doi.org/10.1007/s11804-024-00405-6

RESEARCH ARTICLE

Review of Vibration Analysis and Structural Optimization Research for Rotating Blades

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Received: 11 January 2024 / Accepted: 02 March 2024

Abstract

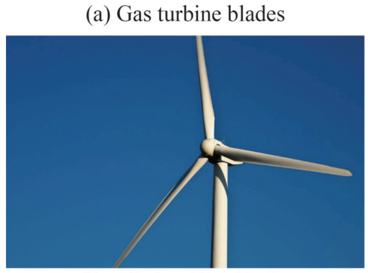
Blades are important parts of rotating machinery such as marine gas turbines and wind turbines, which are exposed to harsh environments during mechanical operations, including centrifugal loads, aerodynamic forces, or high temperatures. These demanding working conditions considerably influence the dynamic performance of blades. Therefore, because of the challenges posed by blades in complex working environments, in-depth research and optimization are necessary to ensure that blades can operate safely and efficiently, thus guaranteeing the reliability and performance of mechanical systems. Focusing on the vibration analysis of blades in rotating machinery, this paper conducts a comprehensive literature review on the research advancements in vibration modeling and structural optimization of blades under complex operational conditions. First, the paper outlines the development of several modeling theories for rotating blades, including one-dimensional beam theory, two-dimensional plate–shell theory, and three-dimensional solid theory. Second, the research progress in the vibrational analysis of blades under aerodynamic loads, thermal environments, and crack factors is separately discussed. Finally, the developments in rotating blade structural optimization are presented from material optimization and shape optimization perspectives. The methodology and theory of analyzing and optimizing blade vibration characteristics under multifactorial operating conditions are comprehensively outlined, aiming to assist future researchers in proposing more effective and practical approaches for the vibration analysis and optimization of blades.

Keywords Rotating blade; Vibration characteristics; Structural optimization; Harsh operating conditions; Review

1 Introduction

Rotating machinery, ranging from marine gas turbines to offshore wind turbines, as shown in Figure 1, is widely used in marine engineering fields. As a crucial component of rotating machinery, blades undertake the responsibility of energy conversion. Any minute vibration of blades can potentially have a nonnegligible impact on the entire rotating mechanism. As depicted in Figure 2, blades have the highest probability of failure in rotating machinery, and among all failures, high-cycle fatigue caused by vibration accounts for the largest proportion. Therefore, establishing a vibration analysis model and researching the vibration characteristics of blades hold considerable importance.

(a) Gas turbine blades



(b) Wind turbine blades

Figure 1 Common blade models in marine engineering fields

The progression of rotating machinery, marked by increasing rotational speeds, higher pressure ratios, and enhanced

Article Highlights

- This paper focuses on the advancements in the vibration analysis and structural optimization of rotating blades.
- Three vibrational modeling theoretical methods for rotating blades are presented.
- Relevant literature on blade vibration within the context of different environmental factors, encompassing thermal conditions, aerodynamic loads, and crack factors, are reviewed.
- Structural optimization of blades refers to shape optimization and material optimization in this work.

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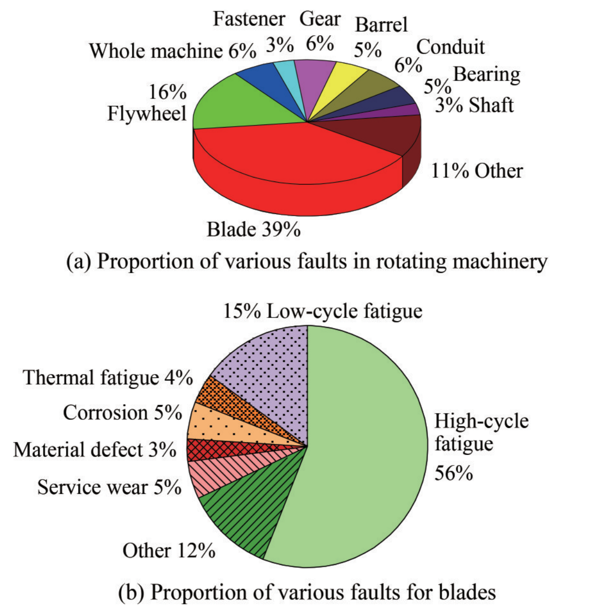


Figure 2 Proportion of various faults for rotating mechinery and blade part (Liu, 2016)

operational efficiency, introduces novel challenges for the optimal operation of blades. The operational environment of blades has become increasingly rigorous, with centrifugal forces, aerodynamic loads, and high-temperature conditions altering blade vibration characteristics. Considering the effects of these loads in isolation is no longer sufficient for accurately representing the working conditions of blades. In addition, the drive to improve the efficiency and strength of blades has made the shape more complex. The variable blade profiles, pre-twisted angles, and presetting angles collectively contribute to the increasing difficulty of blade vibration modeling. As the central components of the mechanism, blades are vulnerable to high-cycle fatigue induced by various loads during their operational process. Consequently, they emerge as a primary component prone to failure, whose dynamic characteristics influence the overall reliability of the entire rotating machinery. In this context, numerous scholars have sought a precise model for solving blade vibration under multivariable operating conditions. The influence of temperature environments, aerodynamic loads, variable blade profiles, and crack factors on the vibration characteristics of blades is explored.

To prevent blade cracks, reduce vibration failures, and enhance blade operational performance, optimizing the design of blades becomes paramount. The structural optimization design of blades focuses on structural strength, aerodynamic efficiency, and vibration characteristics. By combining mechanical analysis with mathematical optimization algorithms, an iterative process is employed to change the topology, shape, and dimensions of blades, with the ultimate aim of proposing an optimal design solution to achieve specific blade performance. In the blade design process, first, designers establish a preliminary blade structure in modeling software. Second, analytical calculations are conducted within structural analysis software. Finally, on the basis of prior experience, designers assess the obtained analytical results and iteratively modify the blade structure until it satisfies the desired operational conditions. The described procedure heavily depends on the experience of designers, and the frequent interactions between different platforms consequently elongate the entire blade design cycle (Chen et al., 2006; Ma et al., 2008; Lv et al., 2022).

With the rapid development of computational mechanics, numerical simulation methods are increasingly becoming indispensable tools in optimization design research. Furthermore, optimization design and analysis based on numerical simulation typically involve two or more different software tools. In recent decades, numerous studies have introduced various optimization algorithms and established a wide range of blade optimization models, conducting investigations into the structural optimization of blades. This paper mainly focuses on the recent development and applications of vibration analysis and optimization design models for blades. In particular, the vibration problems of blades under harsh operating conditions are reviewed and the future development direction is discussed.

2 Vibration analysis models for rotating blades

Blades, as vital parts of rotating machinery, have always been a key focus for engineers. Because the bending stiffness of the hub in rotating machinery far exceeds that of the blades, vibrations occurring within the machinery tend to manifest more as characteristics of blade vibration. Hence, in theoretical research, the vibration analysis model for an individual blade is customarily established first, and then the connection relationship between blades and hubs is considered under various boundary conditions. Throughout decades of development, scholars have made considerable advances in the study of vibrational behaviors of rotating blades, establishing numerous vibration analysis models.

2.1 One-dimensional blade model

In the early stages of research, the displacement characteristics of blades during vibration must be grasped to address the damage caused by blade vibration in rotating machinery. Consequently, early scholars tended to overlook certain detailed blade characteristics and focused exclusively on the primary structural attributes of blades. This tendency gave rise to the creation of a simplified theoretical model known as the rotating beam model, which ensures computational efficiency while effectively capturing the fundamental vibration characteristics of blades. As the most fundamental beam theory, the Euler–Bernoulli beam theory was initially applied in the vibration modeling of rotating blades. Considering axial motion based on Bernoulli beam theory, Lee (1995) derived differential vibration equations in matrix form for the rotating cantilever beam. Yoo et al. (1995) proposed a vibration solution model based on hybrid deformation variables to simplify the derivation process and show the nonlinear motion relations more clearly than the traditional Cartesian coordinate system model based on nonlinear geometric relations. Therefore, many scholars have extended the model to homogeneous and functionally graded (FG) rotating beam models considering pre-twisted angles (Yoo et al., 2001; Remesh and Mohan Rao, 2013), as shown in Figure 3, both of which have obtained relatively accurate results. Pesheck et al. (2002) established an invariant flow reduced-order model based on the uniform Euler beam theory, embedding nonlinear effects between linear modes, including important axial – transverse vibration coupling. The results show that although transverse motion is the dominant vibration mode of the beam model, vibrations in other directions, including axial extension, also need consideration. Yang (2004) considered the centrifugal stiffening effect caused by rotation with the coupling between elastic deformation and the rigid motion of the hub. They derived a fully coupled nonlinear integro-differential equation that describes axial, transverse, and rotational Bernoulli beam motion. Based on this model, certain control rules for blades were proposed. With the rotating Euler–Bernoulli beam model, Zhao and Wu (2017) focused on the Coriolis effect and axial tensile deformation induced by rotational velocity on the vibration characteristics. Hamdan and El-Sinawi (2005) modeled a rotating flexible Euler beam fixed to a rigid hub with a certain setting angle, and the displacement coordinates of any point on the beam model were obtained using two coordinate transformations. Özdemir and Kaya (2006) studied the vibration characteristics of a rotating cantilever variable-section Euler–Bernoulli beam, assuming that the beam model has a rectangular cross-section that changes linearly along the x-direction, as shown in Figure 4. The results showed that increasing the taper ratio of the cross-section initially reduces the natural frequency of the rotating beam. When this ratio is greater than the critical taper ratio, the frequency change trend is the opposite.

Ondra and Titurus (2019) considered rotating pre-twisted blades with movable ribs and explored the frequency characteristics of the beam–movable rib model based on Bernoulli beam theory. Kim et al. (2013) proposed a new way to solve the centrifugal strengthening effect for rotating Euler beams. This model can not only solve the frequencies of the beam model but also obtain the time domain responses. In this study, the academics noted that the centrifugal stiffening effect of rotating beams can be solved in three ways: mixed deformation variables using a non-Cartesian coordinate system, centrifugal work potentials, and

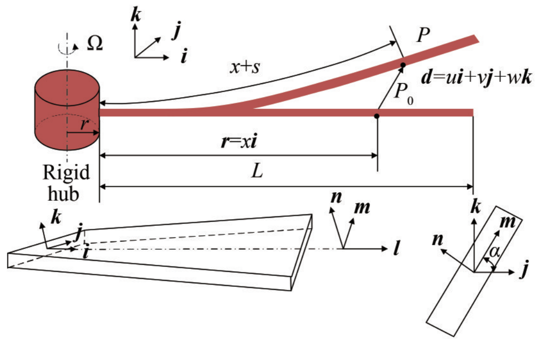


Figure 3 Vibration solution model for the rotating beam based on hybrid deformation variables (Ramesh and Rao, 2013)

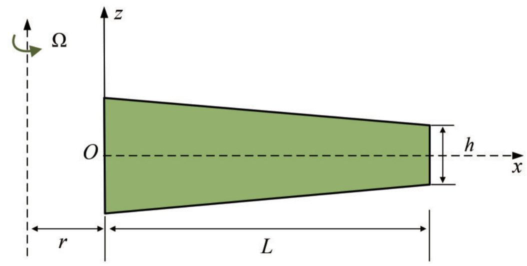
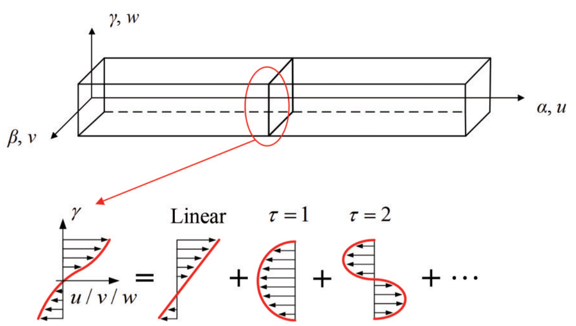


Figure 4 Variable thickness cross-section of the rotating beam model (Özdemir and Kaya, 2006)

nonlinear stress–strain. With the emergence of new materials, researchers began to propose rotating Euler–Bernoulli beam models of various nonuniform materials, establishing a series of vibration analysis models such as rotating single-directional functionally graded beams (Elishakoff et al., 2015), functionally graded pre-twisted beams (Fang et al., 2018), bidirectional functionally graded beams (Oh and Yoo, 2016), and multilayer composite beams (Jafari-Talookolaei, 2015).

Although the Euler–Bernoulli beam theory is simple in form, it ignores transverse shear deformation and rotational inertia effects, which easily makes the frequency value overpredicted. On this basis, scholars have developed rotating beam models based on various refined beam theories. Subrahmanyam et al. (1982) employed the Reissner and potential energy methods to develop a rotating beam model that considers shear deformation and inertial effects. Their findings indicated that shear and inertial effects indeed result in a reduction of frequency, particularly at higher frequencies. Researchers have subsequently developed various rotating Timoshenko beam models based on numerical and analytical methods, mainly including the finite element method (Rao and Gupta, 2001), the differential transformation method (Ozdemir Ozgumus and Kaya, 2010; Rajasekaran, 2013), the differential quadrature method (Bambill et al., 2010), the Rayleigh–Litz method (Zhu, 2011), and the Litz method considering local hierarchical functions (Dangarwala and Nagendra, 2023). Utilizing the finite element method, Deng et al. (2006) specifically investigated the coupling effects of transverse and longitudinal deformations, transverse inertia force, and axial centrifugal force on the modal frequencies of Timoshenko beam structures under rotational conditions. In the context of aircraft engine blades, Wang (2017) formulated the vibrational control equations for a Timoshenko beam in a rotating coordinate system and systematically studied the influence of parameters such as the presetting angle, taper ratio, and pre-twisted angle on the vibrational traits of the rotating model. Carrera proposed Carrera's unified formulation (CUF), which can obtain different beam theories by changing the size of the expansion series. CUF was, therefore, used to establish a rotating beam model (Carrera et al., 2013). As shown in Figure 5, Chen et al. (2021a) proposed a quasi-3D rotating functionally graded beam model by combining the CUF theory with an improved Fourier spectral method. In currently available methods, the effects of warping and cross-sectional deformation can be obtained by employing the generalized shear deformation beam theory (Chandiramani et al., 2002; Hu et al., 2020). The strengths and weaknesses of different rotating beam theories are displayed in Table 1.



$$u(\alpha,\beta,\gamma)=u_0(\alpha,\beta)\gamma^0+u_1(\alpha,\beta)\gamma^1+\cdots+u_n(\alpha,\beta)\gamma^n=\sum_{\tau=0}^{n}u_\tau F_\tau$$

$$v(\alpha,\beta,\gamma)=v_0(\alpha,\beta)\gamma^0+v_1(\alpha,\beta)\gamma^1+\cdots+v_n(\alpha,\beta)\gamma^n=\sum_{\tau=0}^{n}v_\tau F_\tau$$

$$w(\alpha,\beta,\gamma)=w_0(\alpha,\beta)\gamma^0+w_1(\alpha,\beta)\gamma^1+\cdots+w_n(\alpha,\beta)\gamma^n=\sum_{\tau=0}^{n}w_\tau F_\tau$$

Figure 5 Rotating beam model based on the CUF method (Chen et al., 2021a)

2.2 Multidimensional blade model

Sometimes, scholars still employ the rotating beam model to systematically study blade vibrational characteristics when the effects of the detailed features are not of concern. However, many rotating machines tend to have a small aspect ratio, and only considering the vibration displacement in one direction cannot accurately predict the vibration characteristics. Furthermore, certain blade details (as shown in Figure 6), such as the presetting and pre-twisted angles, cannot be accurately represented in blade frequencies and mode analysis solely using one-dimensional models. Therefore, the application of two-dimensional plate–shell theory began constructing vibration analysis models for blades with small aspect ratios.

Sun et al. (2013a) established a rotating blade model with arbitrary presetting angles based on classic plate theory and the proposed fast configuration method. Rostami (2018) considered the vibration characteristics of an anisotropic rotating cantilevered thin plate and comprehensively discussed the effects of stiffness ratio, rotational speed, presetting angle, hub radius, and aspect ratio on the vibration characteristics. Chen et al. (2019) researched a classical plate structure that considers large deformations due to rotation based on the absolute coordinate formulation. Using the shallow shell theory, Li and Cheng (2021) developed a variable thickness blade model considering the pre-twisted angle. This model is tapered in the spanwise direction of the blade, one of the most used equivalent forms of variable thickness blade. Using the thin shell theory, Chen and Li (2019) proposed a rotating pre-twisted shell model that considers multilayer composite materials. Because the presetting and pre-twisted angles are considered, the displacement deformation of any point in the blade is obtained after several coordinate transformations. Das and Karmakar (2018) applied the shallow conical shell theory to model rotating blades. In this work, they established a vibration solution model for rotating shells made of FG materials varying in thickness direction and explored the effects of different material combinations on the first two frequencies of the model. Apart from the classical plate and shell theory, the first-order shear deformation theory has found extensive application in blade vibration modeling. After establishing a classical plate blade model, Sun et al. (2013b) derived the vibration control equations of a pre-twisted blade under rotating conditions with the thick shell theory. Liu et al. (2018) provided a dynamic model for a rotating sandwich FG shell to explore the frequency steering phenomenon under the influence of rotational velocity by considering

Table 1 Comparison of different rotating beam models

Methodology	Strengths	Weaknesses
Euler–bernoulli beam	Low computational load	Ignores transverse shear forces
Timoshenko beam	Considers shear deformation	Requires shear factors
Generalized shear deformation beam theory	Considers high-order shear deformation, including cross-sectional warping effect deformations	Unclear physical interpretation; increases computational complexity
CUF theory	Provides a unified framework; achieves arbitrary precision	Substantially increases the mathematical and computational complexity; requires practical application validation

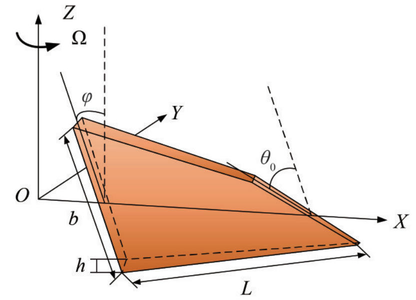


Figure 6 Rotating plate model with a setting angle φ and a pre-twisted angle θ_0

the centrifugal force and the Coriolis force effect. Scholars also applied the first-order shear cylindrical shell theory to the vibration modeling of the blade. Combining different methods, the carbon nanotube-enhanced FG (Lei et al., 2015) and graphene-enhanced FG rotating blade models (Niu et al., 2019) were established. In Figure 7, the isogeometric approach was combined with higher-order shear deformation plate theory by Ansari and Setoodeh (2020), wherein the high-order continuous non-uniform rational B-spline (NURBS) basis functions were used to describe the linear and nonlinear variations in the blade's thickness in the spanwise or chordwise directions. The effects of various shape parameters and means of thickness variation on the static frequencies of the blade were investigated; however, the rotation speed of the blade was neglected in this study.

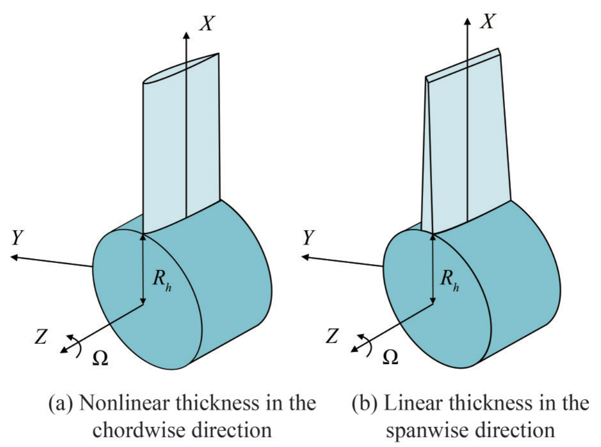


Figure 7 Two variable thickness blades with linear and nonlinear variations in the spanwise and chordwise directions, respectively (Ansari and Setoodeh, 2020)

With the advancement of mechanical theories and the growing engineering demand, engineers have progressively sought high-fidelity models for blade vibration. To capture vibrating blade deformations comprehensively, consideration of the degrees of freedom along each direction is essential. Thus, the three-dimensional blade model or quasi-three-dimensional blade models need to be developed. Chen et al. (2021a, 2022a, 2022b) coupled the CUF theory with an improved Fourier series to develop a quasi-three-dimensional model for rotating blades. By representing the two-dimensional in-plane coordinates with an improved Fourier spectral method and expanding the transverse displacement with a Taylor series, the expressions for stress–strain in all three dimensions were derived. The results demonstrated that the established model can accurately predict the vibrational behavior of blades. Chen (2021) combined three-dimensional elasticity theory with the isogeometric approach to establish vibrational analysis models for rotating plates, partial cylindrical shells, and conical shells, thoroughly discussing the influence of structural parameters on the dynamic behaviors of the developed models (as shown in Figure 8).

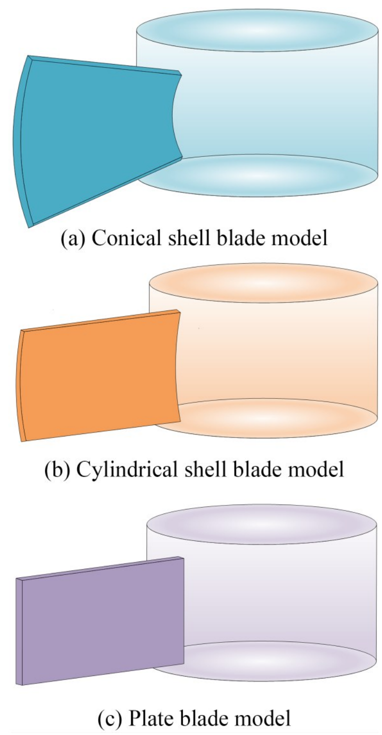


Figure 8 Commonly used simplified blade models

Accurate prediction of the vibrational characteristics of blade structures is closely linked to high-fidelity vibration analysis modeling. Comparison of different blade models are shown in Table 2. Based on the literature review above, the key conclusions are as follows:

• Compared to one-dimensional beam models, two-dimensional plate–shell models and three-dimensional models more accurately represent blade deformation and displacement during vibration.

• The vibration characteristics of blades are considerably affected by factors such as the presetting angle, pre-twisted angle, and shape features with varying thickness.

• When addressing the above factors, most literature generally requires transformations between multiple coordinate systems, further complicating the derivation and solution of blade vibration governing equations.

Table 2 Comparison of different blade models

Model type	Applicability	Strengths	Weaknesses
One-dimensional model	Large aspect ratio blade	Theoretical simplicity, ease of solution	Ignores shear deformation, focuses on transverse vibration
Two-dimensional model	Small aspect ratio blade	Accounts for shear deformation, considers in-plane vibration	Coordinate transformation is cumbersome, theoretical derivation is complex
Three-dimensional model	All blades	All-directional displacements are considered, high model fidelity	High computational workload, lacks a comprehensive methodological framework

• Two-dimensional plate–shell structures are limited to addressing equivalent thickness forms of blades that can be represented using mathematical functions. Few researchers have considered establishing vibration theoretical solution models for blades with varying cross-sections.

3 Research on blade vibration characteristics in multifactorial operational conditions

Blades operate in harsh conditions, particularly for gas turbomachinery compressors and turbine blades, which frequently endure the effects of high-temperature and high-pressure airflow. The thermal stress and aerodynamic loads inevitably affect the vibration characteristics of the blades. Therefore, the vibration characteristics of rotating blades in multifactorial operational environments have already become another research interest.

3.1 Thermal environment

The influence of temperature on blade structures is categorized into steady-state thermal environments and thermal shocks. A steady-state thermal environment refers to a system in a constant thermal state in which the input and output of thermal energy are in equilibrium. When an object is placed in a constant temperature environment, its heat energy exchange with the environment reaches a steady state. In this state, the heat energy exchange rate between the thermal energy inside the object and the environment is equal, so the temperature of the object does not change with time. When the time scale of the thermal environment on blade vibration is smaller than the time scale of temperature change, the thermal environment can generally be considered stable. Thus, this paper focuses on a steady-state thermal environment without a heat source in the system.

The effects of steady-state thermal environments on structures mainly have two manifestations: first, the temperature changes material mechanical properties, such as elastic modulus, density, and Poisson's ratio, which affects the structural load-bearing capacity. Second, the uneven temperature distribution generates thermal stresses under boundary constraints. Most current research discusses the vibration characteristics of blades in thermal environments from these two perspectives.

Librescu et al. (2008) considered thin-walled rotating beam structures in high-temperature environments, focusing on the effect of the temperature-dependent functional gradient materials distribution on the bending-torsion coupled vibrations. Paruda and Mohanty (2019) used high-order shear deformation theory and von Karman's theory to explore the influence of temperature conditions, presetting angle, and rotation speed on the linear and nonlinear vibration frequencies of cantilever plates. Using the nonlinear heat transfer equation, Oh and Yoo (2020) established a model for static and dynamic analyses of rotating blades, which considers the cooling channel. The study findings indicated that the nonlinear heat transfer equation represents the temperature distribution more precisely than linear equations. The external gas temperature substantially impacts the natural frequencies, while the internal cooling temperature exerts a pronounced influence on the axial displacement of the rotating blades. Ansari et al. (2020) proposed a systematic stepwise solution method for analyzing the vibration behavior of rotating FG variable thickness blades in high-temperature environments, as shown in Figure 9. In the first step, the static response of the blade under thermal stress loading is considered. Then, the displacement deformation obtained is carried over to the second step, where the centrifugal and Coriolis effects due to rotation are considered to obtain the vibration characteristics of a variable thickness blade in the thermal environment. Notably, this paper neglects the effect of temperature on material properties. Deb Singha et al. (2021) and Rout et al. (2021) represent the rotating blade as a partial conical shell with temperature changes uniformly or linearly and nonlinearly along the thickness direction, as shown in Table 3. On this basis, the influence of the temperature gradient on blade frequencies under various temperature changes was studied. Thermal barrier coating (as depicted in Figure 10) is one of the main ways to reduce the surface temperature of the blade. Cao et al. (2017) represented the blade with thermal barrier coating material as a sandwich plate and shell structure with a pre-twisted angle to investigate the effect of different coating materials and coating thickness on the frequencies of the blade in a thermal environment. Chen et al. (2021b) developed a new FG laminated rotating blade model that uses a novel approach for solving thermal stresses to investigate the dynamic behavior of rotating blades in a steady-state thermal environment. In this environment, the thermal stress effect on the blade vibration characteristics is unsubstantial. Thus, the thermal stress load can be neglected and only the effect of temperature on the material is considered.

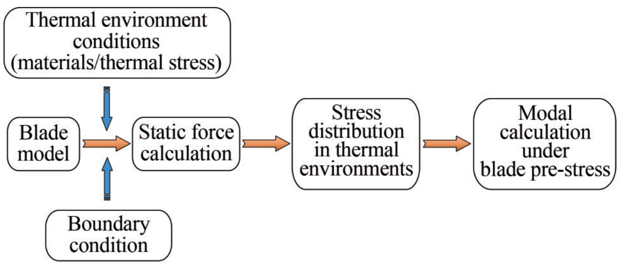


Figure 9 Two-step solution strategy for blade vibration analysis in thermal environments

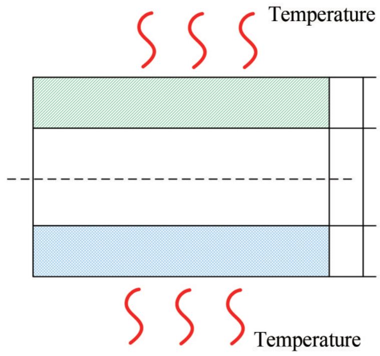


Figure 10 Equivalent model of sandwich materials with thermal barrier coatings

3.2 Aerodynamic load

In addition to temperature loads, the forced vibration and flutter problems of blades under aerodynamic loads have always gained attention from scholars in the field of rotating machinery. With increasing demands on blade performance, the pressure ratio of the blades increases, and the blades become thinner, exacerbating the above problems. Flutter, as a type of self-excited vibration coupled with aerodynamic, inertial, and elastic forces, occurs frequently during rotating machinery operation. Therefore, earlier prediction methods for blade flutter boundaries have emerged (Zhang et al., 2011). Initially, most of the empirical or semi-empirical and semi-theoretical models (as shown in Figure 11) for flutter vibration analysis were used in engineering (Tao et al., 1991; Zhou, 1992), which rely on extensive experimental data and, therefore, are not universally applicable. Later, with the development of numerical methods, the introduction of various numerical prediction methods into the flutter boundary analysis began. It can be roughly divided into two categories: flutter analysis models based on fluid–structure decoupling methods and fluid–structure coupling methods. Fluid–solid decoupling of the blade aeroelastic problem means that the aerodynamic and dynamic problems are separated and simplified separately. Therefore, aerodynamic analysis methods and dynamic analysis methods are derived.

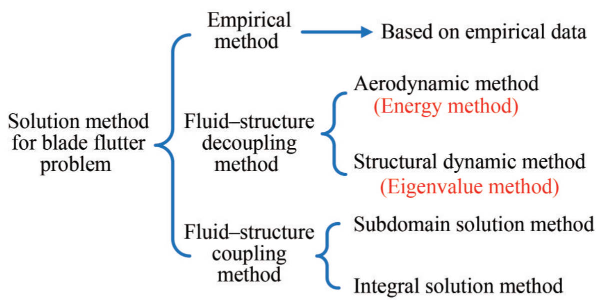


Figure 11 Solution method for the blade flutter problem

Numerous aerodynamic models have been proposed, including linear models (Verdon and Caspar, 1984; Kodama and Namba, 1991) and nonlinear models (Gerolymos et al., 1990; Ekici et al., 2005). On the basis of aerodynamics models, scholars have expressed aerodynamic loads as a function of displacement or velocity to obtain aerodynamic work, which is added to the vibration control equations (Kielb and Ramsey, 1988; Sun et al., 2008, Wang et al., 2023) to study the vibration characteristics of blades. This method is called the dynamic method. Recently, the rapid development of computer science has enabled the use of software for fluid–structure coupling simulation of blades (Moffatt and He, 2003; Zhang et al., 2009; Xiao et al., 2006;

Table 3 Three commonly used temperature distributions along the thickness direction

Distribution ways	Characteristics	Mathematical expression
Uniform	Temperature remains constant across the entire thickness	$T = T_0 + \Delta T$
Linear	Temperatures on the upper and lower surfaces of the blade are different and constant, with a linear variation in temperature along the thickness direction	$T(Y) = T_b + \left(\frac{Y}{h} + \frac{1}{2}\right)(T_t - T_b)$
Nonlinear	Temperature distribution in the thickness direction satisfies the one-dimensional steady-state heat conduction equation and presents a nonlinear distribution	$T(Y) = \frac{(\Delta T)}{C} \sum_{s=0}^{5} (-1)^s \frac{(K_t - K_b)^s}{(p+1)K_b^s} \left(\frac{Y}{h} + \frac{1}{2}\right)^{p+1} + T_b$ $C = 1 + \sum_{s=1}^{5} (-1)^s \frac{(K_t - K_b)^s}{(p+1)k_b^s}$

Wu, 2005; Zeng, 2006). By establishing a model in numerical software and setting corresponding solution methods, the flutter characteristics of the blades under different flow fields can be obtained. Most of the above studies focus on stall flutter and non-stall flutter (as shown in Figure 12) of blade flutter. In non-stall flutter, there is a bending-torsional mode coupled flutter (Su, 2017), which refers to a phenomenon that the bending and torsion modes of the blade gradually approach as the aerodynamic force increases, causing instability. As the blade speed increases and the use of asymmetric blades widens, this type of flutter becomes more common (Verdon, 1993) and has gradually been investigated (Rządkowski and Gnesin, 2007; Sadeghi et al., 2013; Yang et al., 2005; Wu, 2016).

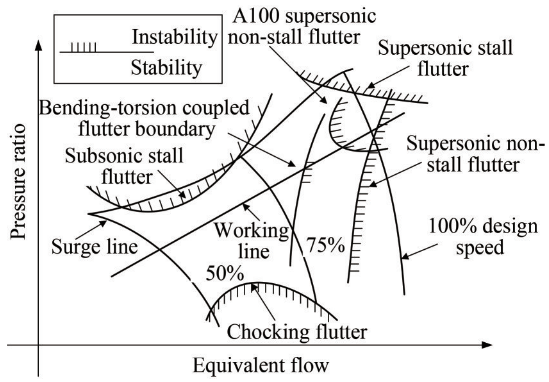


Figure 12 Common flutter boundary types (Su, 2017)

As mentioned above, the exploration of blade vibration under thermal and pressure loads has been considerable. The following findings are notable:

• At present, most studies on blade flutter are based on simulation software. A few aeroelastic coupling analysis models of blade structure are limited to the conventional plate and shell shapes, such as a square plate, a rectangular plate, some cylindrical shells, and double curvature shells, without considering the variable thickness shape of the actual blade structure.

• Although researchers have conducted studies on the vibration characteristics of new composite blades in thermal environments, the flutter physical mechanism of the composite blades is unknown and requires further exploration.

• The coupling effects of temperature, aerodynamic pressure, and variable thickness shapes must be considered. A flutter boundary analysis model of variable thickness aero–thermal – elastic coupled blades is needed to explore the coupling influence on the flutter boundary.

3.3 Cracked factor

Cracks often form in operating blades after long-term exposure to static and dynamic loads such as thermal stresses, centrifugal forces, and airflow pressures. The occurrence of cracks greatly affects the vibrational characteristics of the blade. Cracks with different depths and positions have different effects on blade frequencies. The change in frequency determines the location and state of the crack. Therefore, a precise vibrational analytical model for cracked blades holds considerable engineering implications for the early prediction and diagnosis of blade crack failures. From a macro perspective, the crack of the blade can be represented by two models: the breathing crack model and the open crack model. The breathing crack model has a nonlinear characteristic, which varies between open and closed states, as depicted in Figure 13.

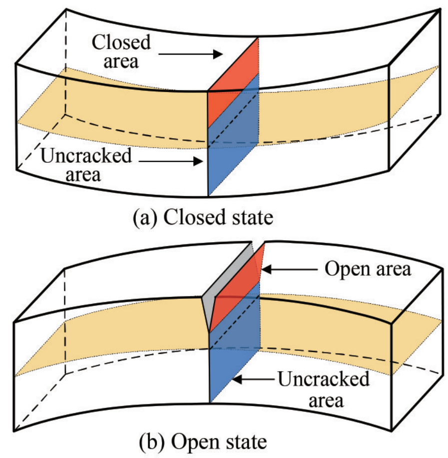


Figure 13 Breathing cracked beam model (Yang et al., 2010a)

Initially, scholars proposed various mathematical analysis models to describe the crack effect based on beam theory. Using Green's function method, Zhao et al. (2016) developed a cracked Euler–Bernoulli beam model to investigate the forced vibration response under harmonic forces. For fully embedded horizontal cracks, Liu et al. (2016a, 2016b, 2016c) proposed a cantilever three-segmented beam model that considers the localized flexibility of the crack tip. All three-segmented beam models were established using the Euler – Bernoulli beam theory. This linear model neglects the nonlinear effects at the crack but can more accurately describe the crack effects at the crack tip. Al-Said et al. (2006) formulated a simplistic mathematical model for characterizing the transverse vibration of a rotating cracked Timoshenko beam. This model was used to examine the impact of crack depth, rotational speed, and shear deformation on the natural frequencies of the beam. They found that the frequency difference between a cracked Timoshenko beam and a cracked Euler–Bernoulli beam is a monotonically increasing function of crack depth. Consequently, neglecting shear effects leads to an underestimation of the frequency changes caused by cracks. Following this study, the team (Masoud and Al-Said, 2009) improved the model by considering not only the effects of cracks on the slope of the beam but also the influence on lateral deformation. With the one-dimensional beam model, several scholars

(Chaudhari and Maiti, 1999; Ke et al., 2009; Kitipornchai et al., 2009; Loya et al., 2006; Krawczuk et al., 2003) represented cracks as massless linear and rotational springs to simulate the effects on the stiffness of the model (as illustrated in Figure 14). The investigation revealed that even small cracks can induce measurable changes in higher-order frequencies. A detailed exposition and comparative analysis of various recently proposed breathing crack beam models was conducted by Yang et al. (2021a, 2021b). They thoroughly discussed the applicable scenarios, advantages, and disadvantages of various crack models. In this study, they highlighted the key characteristics of these models and provided recommendations for selecting appropriate models under specific conditions.

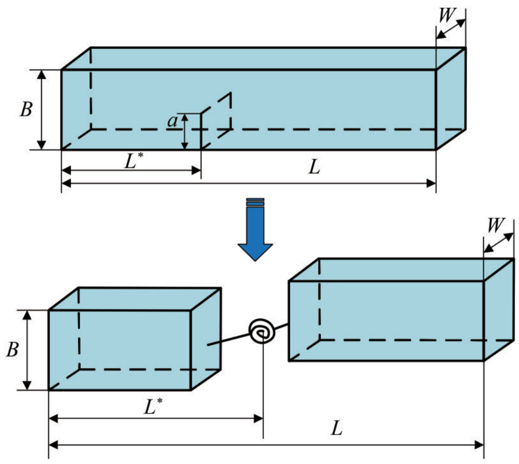


Figure 14 Equivalent cracked beam model with massless springs (Loya et al., 2006)

The finite element method (FEM) has also been widely used to establish cracked blade models as depicted in Figure 15 (Fernandes et al., 2016; Hou and Lu, 2017; Chen and Tsai, 2014; Shukla and Harsha, 2016; Cui and Wang, 2015). However, because of the continuous basis functions used in FEM, which cannot directly represent the presence of cracks, there is often a need to refine the mesh and increase the number of elements around the crack. Consequently, the extended finite element method (XFEM) has been developed on the foundation of traditional FEM, along with new elements suitable for addressing discontinuities in problems. Bachene et al. (2009) developed the FORTRAN language of XFEM and established a rectangular plate model with boundary and middle cracks. The enrichment functions are applied to handle crack-tip elements and elements divided by cracks, proving that XFEM effectively addresses cracked plate and shell problems. In addition, Schwerdt et al. (2017) used XFEM to mesh turbine blades with cracks. The p-type finite element and high-order finite elements were employed by Yu and Chu (2008) and Cheng et al. (2011), respectively, to establish a tapered beam model with cracks, wherein high-order polynomials were used to represent the transverse displacement of the beam. They separately investigated the vibration characteristics of the cracked beam under static and rotating conditions. Using the strain energy release rate principle, Liu and Jiang (2014) introduced a hexahedral finite element for cracks. This element accounts for stress concentration at the crack tip and introduces breathing functions to address the breathing effect of cracks under variable loads. Compared with the contact element, the proposed crack element can reduce the calculation time while obtaining accurate results.

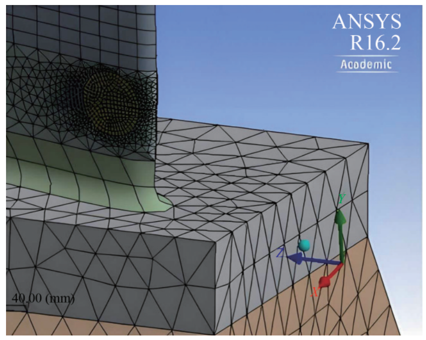


Figure 15 Cracked model using 3D singular crack-tip elements in ANSYS (Fernandes et al., 2016)

In the above studies, most of the literature only considered the case of a single straight crack, while in actual engineering, the rotating blades usually have inclined cracks or multiple cracks and fewer cases of straight single cracks. Therefore, some scholars started to model different types of cracked blades to present their reliable dynamic properties. On the basis of the cracked spring model, Khiem and Lien (2004) developed a multi-cracked beam model and constructed a crack identification procedure using a nonlinear optimization algorithm, which not only identifies the location and length of cracks but also provides the number of possible cracks. Similarly, using a crack rotation spring, Lee and Lee (2017) introduced the transfer matrix method into the Euler–Bernoulli beam model by adding the bending displacement caused by the crack into the equation as a separate transfer matrix. The authors noted that the current method only applies to homogeneous beam structures, necessitating modifications for the extension to nonuniform beams. Donà (2015) proposed a new Galerkin approximation method based on mixed gradient elasticity theory to solve the dynamic characteristics of multi-cracked Euler beams. The authors note that this model can more accurately represent the rotational effects of the beam model at the crack damage site. For inclined cracked beams, Ma et al. (2016) established a hybrid element model based on finite element software. This model uses two-dimensional planar elements at the crack and three-dimensional beam elements at both ends away from the crack. On the basis of this model, the effects of gravity and excitation forces at any angle in the transverse and axial directions on the vibration response of a cracked beam were investigated. Soliman (2020) constructed a finite element beam model for various inclined cracks and investigated in detail the influence of different crack angles on the stiffness, vibration modes, and frequencies of cantilever beams.

From the above literature review, the following notes are apparent:

• The presence of cracks noticeably affects the vibration characteristics of blades. Consequently, modal parameters such as natural frequencies and mode shapes can be employed to assess the initiation of cracks and identify crack-related parameters.

• At present, to model cracked blades, most theoretical models tend to be simple beam models, while cracked plates and shell models or three-dimensional crack models considering large aspect ratios are relatively scarce.

• The finite element simulation method can establish a relatively accurate three-dimensional model, but the mesh processing at the crack is cumbersome, and the calculation cost is large, making the cracked blade difficult to analyze.

4 Structural optimization research for rotating blades

Structural optimization of blades, including shape optimization and material optimization, refers to combining optimization algorithms with analytical models for the physical properties of blades, using a mathematical method instead of the designer's experience to form an automatic optimization process. Through a comprehensive analysis of different blade structures, the optimal blade structure that meets the design requirements is obtained, and the design guidelines of the blade are further developed.

Optimization algorithms can be divided into two main categories: gradient-based algorithms and evolutionary algorithms. Gradient-based algorithms are methods that use the gradient information of the objective function to optimize model parameters. The gradient represents the changing rate of the objective function at a certain point, indicating the steepest ascent direction of the function, which can guide the updating direction of design parameters. Widely used gradient-based optimization algorithms include Stochastic gradient descent (SGD), Momentum, Adagrad, Adam, and Sequential quadratic programming (SQP). Such optimization algorithms converge faster because of the availability of gradient information as a guide for the search direction. However, these algorithms are heavily influenced by the initialization and are usually prone to fall into local optimal solutions. In addition, the fitness and constraint functions must be able to perform a sensitivity analysis, which is quite complex and costly. To avoid these drawbacks, evolutionary algorithms with simpler principles have been developed, which are a class of methods that simulate population evolution to optimize model parameters, such as genetic algorithms, particle swarm algorithms, and differential evolutionary algorithms. This group of algorithms randomly generates candidate solutions within the search domain, has a simple principle, and does not require gradient information. Therefore, it is more suitable for structural optimization of blades considering multiple factors.

Traditionally, alloys have been the most widely used materials for blade manufacturing. However, with the development of materials science and manufacturing technology, advanced materials such as laminated materials and FG materials have emerged. Compared with traditional materials, new materials can achieve high specific stiffness and strength, which are more conducive to lightweighting the blades and adapting them to harsher working environments. The rational design of materials can greatly improve blade performance. Therefore, in recent years, the optimization of material parameters for blades has increasingly emerged as a research hotspot. Material optimization can be considered a specialized form of topology optimization including material selection and material distribution optimization. For laminated blade structures shown in Figure 16, Shiau et al. (1996) developed material optimization models for blades by incorporating optimization criteria methods, feasible direction methods, and improved techniques. The model optimizes the layup thickness of the laminated material by limiting the frequency and the maximum dynamic response deformation to lighten the blade. The optimization results showed that the mass of the optimal blade when the dynamic response is constrained is somewhat larger than the frequency constraint. Moreover, the choice of the initial design for the model considerably affects the optimal design and convergence speed. For gas turbine blades, the high-temperature operating environment makes blade cooling crucial. Frąckowiak et al. (2019) proposed an iterative algorithm to determine the porosity distribution of the material inside the cooling channel for turbine blades. Wind turbines are a main application of the blade structure. Research shows that the cube root of the blades is the maximum stress concentrated and is prone to fatigue fracture. Combining the particle swarm algorithm with the finite element stress calculation model of the blade, Shen et al. (2019) regarded the thickness of the layup as a design variable to minimize the stress in the dangerous zone. Carbon fiber-reinforced composite materials have high modulus and strength and have gradually become an alternative to metal materials in recent years. Xiang et al. (2020) used a partial conical shell with a pre-twisted angle as a simplified model of the blade to explore the optimal plying sequence to maximize a certain frequency. As a heuristic optimization algorithm, the genetic algorithm can obtain accurate results whether the optimal design variables are discrete or continuous, so the author introduced this algorithm into the optimization model and achieved the desired optimization results. Also using this algorithm, Zhang et al. (2022) optimized the ply angle of a helicopter blade using a reduced-order model based on principal component analysis and the radial basis function neural network algorithm.

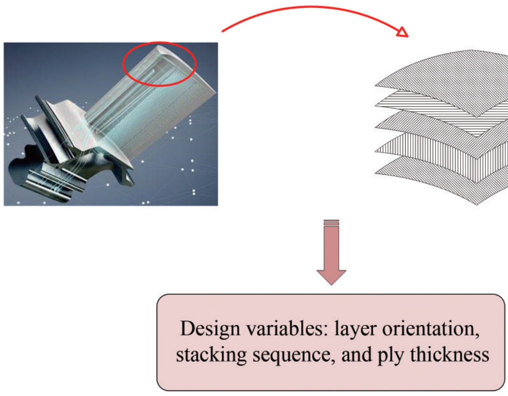


Figure 16 Optimization variables of laminate materials

In contrast to the material optimization design for blades, structural optimization of blades necessitates the establishment of a precise blade model. Otherwise, it may lead to inaccuracies in subsequent computational analyses, which in turn affects the optimization results. Moreover, during the optimization process, the calculation of blade performance is relatively complex, so designers often need to integrate different software to form an optimization platform (Li et al., 2023b; Li et al., 2023a; Aubry et al., 2022), as shown in Figure17.

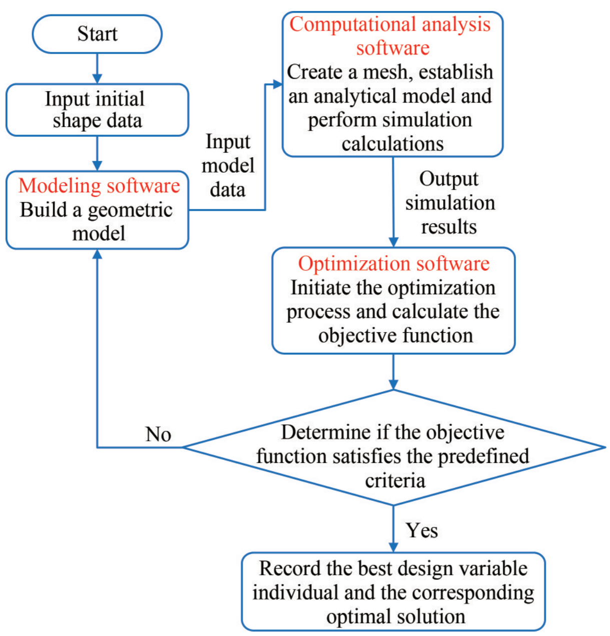


Figure 17 Flowchart of the blade optimization procedure

For an air-cooled turbine, Lu (2014) built a three-dimensional blade aerothermal coupling analysis and optimization design platform by combining several software packages with the commercial optimization collection software ISIGHT. Then, the aerodynamic profile optimization of the static and dynamic blades and the entire turbine with air film cooling was performed, improving aerodynamic efficiency and heat transfer performance. Also using ISIGHT, Chen et al. (2006) introduced three-dimensional modeling into the optimization software by constructing the blade surface profile line and base line with NURBS curves. The simulated annealing algorithm was applied to optimize the shape of the blade to meet the temperature and flow requirements. A new optimization design model for wind turbine blades was proposed by Li et al. (2020). This model considered not only the strength and stiffness but also the noise and work efficiency of the blades. An optimization system for the wind turbine blades was constructed by implementing a multi-objective particle swarm optimization algorithm program in MATLAB, connected with ANSYS for collaborative communication. ANSYS can read the structural parameters optimized by MATLAB for aerodynamic calculations, and MATLAB can obtain the velocity flow field distribution and pressure distribution data calculated by ANSYS for structural optimization. Li et al. (2010) developed an aerodynamic optimization design procedure for 2D viscous turbine blades using the FORTRAN language, which includes parametric modeling of the blade shape using NURBS splines, followed by modeling and analysis in ANSYS software through script files. The adjoint method was applied for the optimization solution, and the CFD software package was simply integrated into the optimization program. Optimizing blades typically involves considerations from various domains such as solid mechanics, structural strength, material mechanics, and fluid mechanics, making it a classical multidisciplinary optimization design problem. To optimize turbine blades in aircraft engines, Yue (2007) developed a multidisciplinary optimization design platform using different design optimization methods. They provided several validated multidisciplinary optimization design solutions for turbine blades. However, multidisciplinary optimization of blades often fails to obtain satisfactory results through single-objective optimization because only one final optimization result is obtained.

Therefore, scholars have begun to incorporate multi-objective algorithms based on the Pareto optimal concept into blade optimization designs. These algorithms provide a set of non-dominated solutions rather than a single "best" solution, known as the Pareto front or Pareto optimal solution set. Because of the introduction of multiple objective functions, the time for each generation of optimization will increase relatively. The computational analysis of blade performance, particularly the fluid analysis, is extremely time-consuming, so people began to develop approximate models (Samad et al., 2008; Luo, 2018; Ju, 2021; Azzam et al., 2017; Du et al., 2022) in the optimization process, that is, using a mathematical model to replace the actual simulation progress (as shown in Figure 18). Wang et al. (2011) combined the multi-objective optimization algorithm NSGA with a back-propagation neural network approximate model, which uses CFD simulation to provide performance evaluation of initial training samples. Comparing the optimization results with those of single-objective optimization based on weighted functions shows that the present framework can not only provide better solutions than single-objective optimization but also provide various alternatives. Li et al. (2019) incorporated the Kriging global surrogate model into the multidisciplinary optimization design framework for cooled turbine blades and proposed an optimization model based on reliability analysis. Luo et al. (2023) combined a supervised machine learning algorithm with an adaptive Gaussian process to establish another surrogate model. This model not only achieved performance prediction for blades but also utilized a multi-objective genetic algorithm to determine the shape of the sweeping blades, with the total pressure ratio and adiabatic efficiency as optimization objectives. Wen et al. (2019) comprehensively provided the process of establishing an aerodynamic optimization design system and platform for turbine blades. They provided detailed explanations of the selection process and principles of constraints, objective functions, and design variables in the optimization design. Additionally, practical engineering applications of the proposed optimization design system were illustrated.

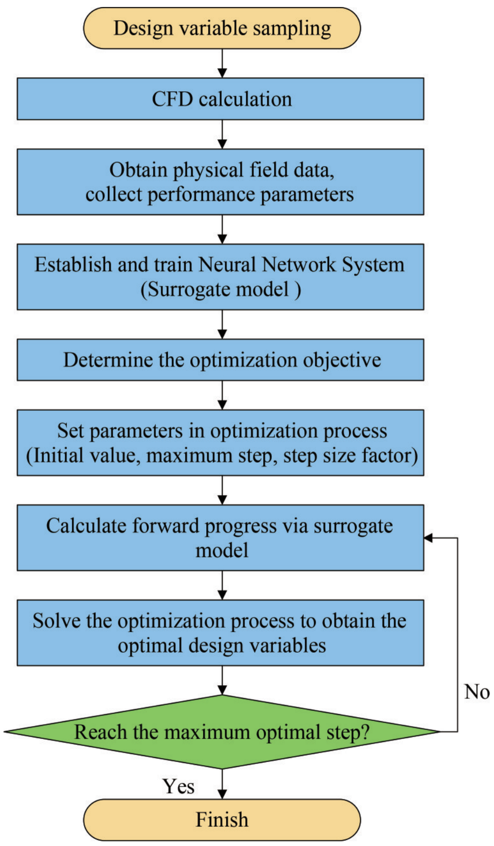


Figure 18 Shape optimization process using surrogate models

The following statements can be made on the basis of the above literature:

• Although advanced materials have recently made considerable progress and are beginning to be applied in rotating machinery, little literature is available on the material optimization design of blades. Effective and unified mathematical material optimization models for blades are lacking.

• Currently, the structural optimization of blades primarily focuses on aerodynamic performance. Undoubtedly, aerodynamic performance is one of the most crucial indicators for blades. However, with the increase in the rotational speed of rotating machinery, the strength, vibration characteristics, and structural mass of blades have become increasingly important.

• As blades operate under multivariable conditions, structural optimization often necessitates frequent transitions between multiple platforms, considerably constraining the progress of the optimization process.

5 Conclusions

This paper aims to thoroughly review scholarly research on the vibration analysis and optimization design of rotating blades. The objective is to provide readers with insights into current trends and research gaps within the domains of blade vibration analysis and optimization design. Building upon this understanding, more complete and effective vibration analysis models and optimization design ideas can be proposed. Because of the limited scope of the author's knowledge, the review of blade vibration characteristics and structural optimization in this paper may not be exhaustive. The work primarily illustrates the advancements in the study of blade vibration and optimization from a modeling perspective.

The abovementioned literature demonstrates that various deformation theories are widely used for vibration modeling of rotating blades. Modeling methods differ in inherent strengths and limitations. Researchers can select an appropriate modeling theory based on specific structural dimensions, the focal aspects of blade vibration, and other relevant considerations. The rotating beam model is suitable for blades with large aspect ratios, while the rotating plate–shell model is suitable for blades with small aspect ratios. The three-dimensional model can simulate the complex shape of the blade and calculate the centrifugal force more accurately, but the computational workload increases.

Furthermore, rotating blades operate in an intricate environment, with centrifugal forces, thermal conditions, and aerodynamic loads that can change the vibration characteristics of the blades. Researchers have proposed many theoretical models for simulating the thermal environment of blades. The solution of the vibration characteristics of blades under aerodynamic loads is mostly based on software. In harsh environments, the generation of cracks considerably impacts the vibration of the blades. Open cracks and breathing cracks are commonly used models to simulate cracks. The vibrational characteristics of cracked blades are usually calculated by segmented beam and rotating spring models as well as FEMs.

This work summarizes the recent progress in blade shape optimization and material optimization. With the development of advanced materials, researchers have begun to heed the influence of material distribution on vibration characteristics, but the corresponding material optimization models for blades remain imperfect. In terms of shape optimization, current research often necessitates the integration of multiple software packages. Although the introduction of surrogate models has substantially enhanced optimization process efficiency, the need for blade structure mesh division and transitions between different software packages still makes the optimization process time-consuming and cumbersome.

6 Future work

With the increasing demand for accuracy in the analysis of blade vibration characteristics in engineering, high-fidelity models for blade vibration analysis are becoming important. The complex shapes of rotating blades, such as the pretwisted angle, presetting angle, variable thickness, and variable cross-section, bring difficulties in solving the centrifugal force of the blade and establishing the vibration analysis model. How to establish a blade model that considers high fidelity but also accurately and efficiently obtains the vibration characteristics of the blade is a problem for future researchers.

The current research on the vibration characteristics of blades under various operating environments is not yet comprehensive enough. Most of the existing literature uses numerical software simulations to consider the vibration and deformation of blades in multifactorial environments, but the complexity of fluid computation makes this method less efficient. Therefore, on the basis of existing research, a new modeling method must be developed that can quickly and accurately obtain the vibration characteristics of blades in complex environments. To model cracked blades, most theoretical models tend to be simple beam models; cracked plates and shell models or three-dimensional crack models considering large aspect ratios have to be established. Moreover, actual blade structures exhibit complex forms of cracks, such as straight cracks, curved cracks, and multiple cracks. Establishing a unified vibration solution model for blades with cracks and exploring the vibration characteristics of blades under different crack forms is a future development direction.

The structural optimization of blades in different environments is gradually becoming a research hotspot. This research primarily has two future directions: implementing multi-objective optimization strategies into the optimization process and improving optimization efficiency and accuracy. The optimal blade configuration not only prioritizes efficiency but also considers other performance metrics, such as vibration and strength. The current optimization platform mainly brings together various software packages, and the mathematical expression of the model differs among these packages, introducing initial model errors and reducing optimization efficiency.

Funding Supported by the National Natural Science Foundation of China under Grant No. 52271309, and Natural Science Foundation of Heilongjiang Province of China under Grant No. YQ2022E104.

Competing interest Guoyong Jin is an editorial board member for the Journal of Marine Science and Application and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no other competing interests.

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