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Design and analysis of steam turbine blades

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Abstract. With the wide application of turbomachinery and the continuous advancement of design technology, steam turbine blade design technology has become an important research field. The level of design is one of the most important factors restricting the performance of steam turbines, which is related to the working efficiency of the steam turbine. This paper systematically introduces the structure of steam turbine blades, analyzes the factors affecting blade operation and design principles, and compares the design of traditional toothed blade root blades with the optimization design of steam turbine blades after improved parameters. Finally, finally, the future design of steam turbine blade is prospected.

Key words: steam turbine; fluid mechanics; steam turbine blade; model; algorithm.

1. Research Progress of Steam Turbine Blades

The turbine blade consists of three parts: the leaf type, the blade root, and the tip of the blade. Each cross-section edge is called a profile line, and the section profile line and its leaf height parameters are in accordance with the requirements of the gas dynamics, meeting the structural strength and processing requirements. It is multi-axial stress state due to load thus must be modeled by three-dimensional solid elements. The establishment of three-dimensional model of blade has a direct influence on the programming of NC machining. The minimum inertia of the section determines the shape of the blade, and the influence of the aerodynamic parameters of the blade on the strength and vibration performance depends on a series of parameters such as the suiting mode of the impeller on the main shaft, the geometric inlet angle of the blade, and the exit angle.

The most important parameters in the design of steam turbine blades are the strength and vibration characteristics of the blades. Foreign countries have made great research in the field of turbine blade optimization and designation. German BMW Engine Company developed a CAD system based on ACIS parametric blade design with the cooperation of Attech Gmbh engineering software technology. NASA and Iowa State University jointly launched the blade modeling CAD system and developed it based on ANSYS software. The turbine blade life analysis software BLADE simulates the blade by using a three-dimensional 8-node isoparametric solid element. Due to the lack of core technology of steam turbines, there are few domestically developed modeling systems in China at present, most of which are based on secondary development of commercial CAD software, such as the blade body surface modeling based on AUTOCAD secondary development of Harbin Institute of Technology and Shenyang Liming Engine Manufacturing Company.



In recent years, with the increasing power of marine steam turbines, the size of the last stage blades of steam turbines has been increasing. Traditional t-leaf roots have been rarely used due to their limited bearing capacity. Instead, they are replaced by eucalyptus roots or teeth Leaf root. However, due to the complicated shape and the large number of mounting faces, it is difficult to analyze the strength by both analytical method and engineering simplification method. The proposed finite element analysis method provides an effective means to solve these complex design analysis problems. It can be used to determine the stress and strain caused by the structure under external load as well as strength check, and is widely applied to determine the extrusion deformation and interference assembly in engineering practice through the elastoplastic model and contact analysis of materials. In this paper, the finite element strength analysis of the tooth tip root and rim of the last stage blade of a marine steam turbine unit is carried out, and the blade root structure is optimized according to the analysis result.

2. Factors Affecting Turbine Blade Design

2.1. Blade Material

The material used for the turbine blades is based on the level of turbine operation. It is divided into three stages: high pressure (HP), intermediate pressure (IP) and low pressure (LP). Blades under high and medium pressure are usually made of stainless steel from 12Cr, but are made of stainless steel at temperatures above 450 degrees, because stainless steel has better properties at high temperatures. The precise choice of materials for low pressure blade applications depends on strength and corrosion resistance. Titanium alloys, especially Ti-6Al-4V, have been used in low pressure turbines since 1960. These alloys are particularly suitable for LP grade blades. Because the density of titanium alloy is less than the density of steel, and this lower density alloy can extend the life of low pressure blades and improve the efficiency of the turbine without increasing stress. Secondly, titanium alloy has stronger corrosion resistance than steel, and LP grade humidity is larger, so titanium alloy is more suitable. Finally, titanium alloys are sufficiently water resistant to be used without corrosion. In general, the nature of the material determines the success or failure of the blade, tensile strength, pressure resistance, corrosion resistance, and elasticity, which determine the load under blade operation.

2.2. Centrifugal Bending Stress

If the gravity center of the blade section and the gravity center of the blade root are not in a straight line at different heights, the centrifugal bending stress is generated. Because centrifugal force acts on the center of mass and periphery of this area, which causes the tensile stress to concentrate on one side of the blade's center of gravity line and the other is compressive stress. The blade is designed to compensate for the airflow load at the center of the tip of the blade, blade designers use the effect of centrifugal bending to counter the effects of airflow bending.

2.3. Load

As the airflow flows through the turbine blades, the airflow pushes the blades to bend them to create a so-called airflow bend. Like centrifugal bending, airflow bending causes the blades to bend longitudinally, creating areas of blade stretching and compressive stress. Although the motion of the airflow does cause the blade to bend, the effect of the airflow bending generated in the blade motion is not as pronounced as the centrifugal force. In fact, the airflow bending stress is usually only 10% of the centrifugal stress. The fixed blade of a reactive steam turbine is more affected by the flow because the force of the airflow on the fixed blade tends to the direction of the moving force of the blade, and the blade cannot be replaced by the force of the air flow. Instead, they react. Airflow bending occurs at three levels of HP, IP and LP, but is most pronounced at the HP level where the pressure difference between the blades is the greatest. At the LP level, airflow bending is also prominent because the LP blade is much longer than HP or IP.

2.4. Dynamic Pressure

Dynamic stress is the vibration of the blades generated in the turbine blades, which are derived from non-uniform flow. For example, nozzle-wake interactions and structural features interfere with airflow. The vibration of the blade leads to the fluctuation of the stress of the blade. If the amplitude of the stress fluctuation is very small, the stress does not exceed the material that the stress can bear, but sometimes it is more than the material of the blade can bear. At a given amplitude, the blades undergo high cycle fatigue, causing them to suddenly fail after a large number of cycles, and greater stress fluctuations will lead to greater stress in the blades. The low cycle fatigue cycles which lead to blade failure are relatively few.

3. Optimization Design of Toothed Blade Root Blade

3.1. The Design Before the Improvement

3.1.1. Geometric Model. The toothed blade root is often used for the end of the steam turbine with high speed, and has the characteristics of high bearing capacity and good safety. The strength analysis and optimization of the blade roots of the last stage blade of a marine high-speed steam turbine were carried out. The working speed of the unit was set to 6500r/min, the root of the last leaf was toothed root, and the length was 180mm. Because of the symmetry of the structure, the basic structural sector in figure 1 is studied.

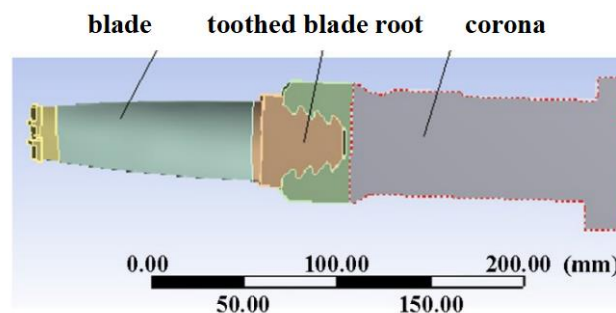


Figure 1. Final blade and wheel geometry

3.1.2. Finite Element Model. The finite element software is used to analyze and calculate the final blade and rim. According to the circumferential symmetry of the blade root and the rim rotation structure, the cycle symmetry structure is used for simplified calculation, that is, the number of blades in the circumferential direction is taken. Due to the great centrifugal force on the blade root and flange, the mesh of the blade root and flange is refined, and the rest of the grid is thicker. The partial enlarged view of the blade root and rim mesh is shown in Figure 2. The total number of cells is set to 94079, the number of nodes is 344324, and the number of blade units is 74095, the number of nodes is 251758, and the number of roulette units 19984, node 92566.

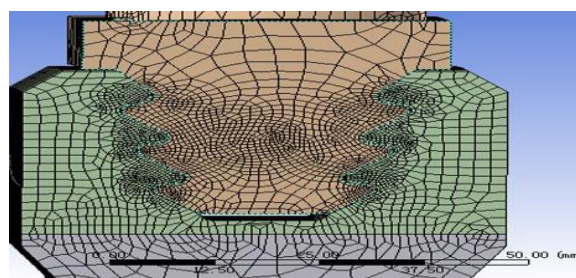


Figure 2. Partial enlarged view of the blade root and rim grid

3.1.3. Loads and Materials. In the calculation, cyclic symmetry constraints are applied to both sides of the fan-shaped model, radial displacement constraints are applied to the inner surface of the rim, and axial displacement constraints are applied to both ends of the rim. The airflow force has a great influence on the dynamic strength of the turbine blade, but the centrifugal force is more important for the static strength. Therefore, in the static strength analysis, only the centrifugal force load caused by the rotation of the structure is considered. According to the state of overspeed 112%, the operating speed is 7300r/min, and the rotational speed load is applied in the direction of rotation of the rotor. The blade material is Cr17Ni4Cu4Nb, and the rim material is 30Cr2Ni4MoV. The load application model is shown in Figure3.

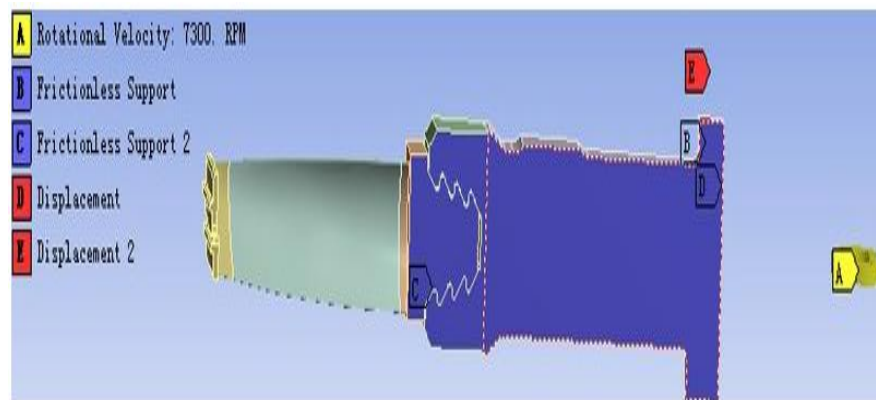


Figure 3. Load .model

3.1.4. Finite Element Analysis and Results. Through calculation, the stress distribution cloud diagram of the rim and the blade under the centrifugal force of rotation is obtained.

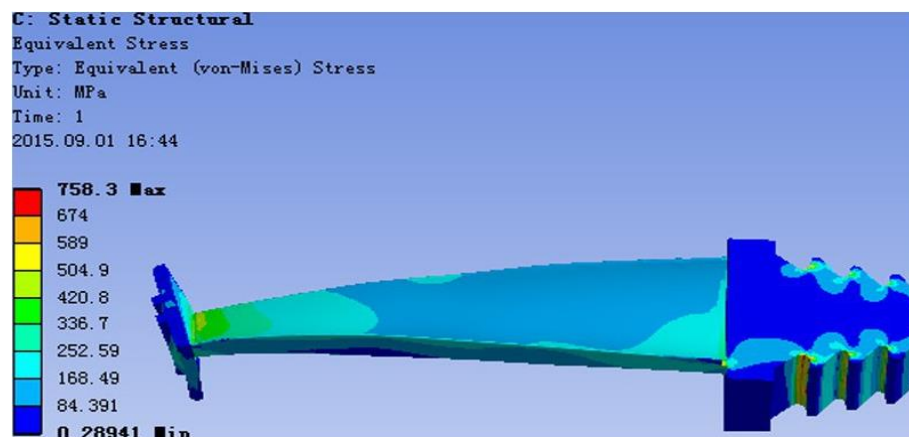


Figure 4. Blade stress distribution cloud map

It can be seen from the calculated stress cloud diagram that the maximum stress of the blade is 758 MPa, which is located at the root of the first tooth. The maximum stress of the rim is 1150MPa, which is located at the root of the lowermost part. The stress level of the middle tooth of the rim is about 720MPa, and the stress level of the uppermost tooth of the rim is about 390MPa. Table 2 gives the maximum equivalent stress of the blade root and the rim and the yield and strength limits of the material. The rotor material is 30Cr2Ni4Mo VA, the strength limit is 860MPa, and the maximum equivalent stress of the rim is 1150MPa, which has exceeded the strength limit of the material. It is

necessary to optimize the structure of the blade root and the rim part to reduce the maximum equivalent stress of the rim, to meet the material strength requirements.

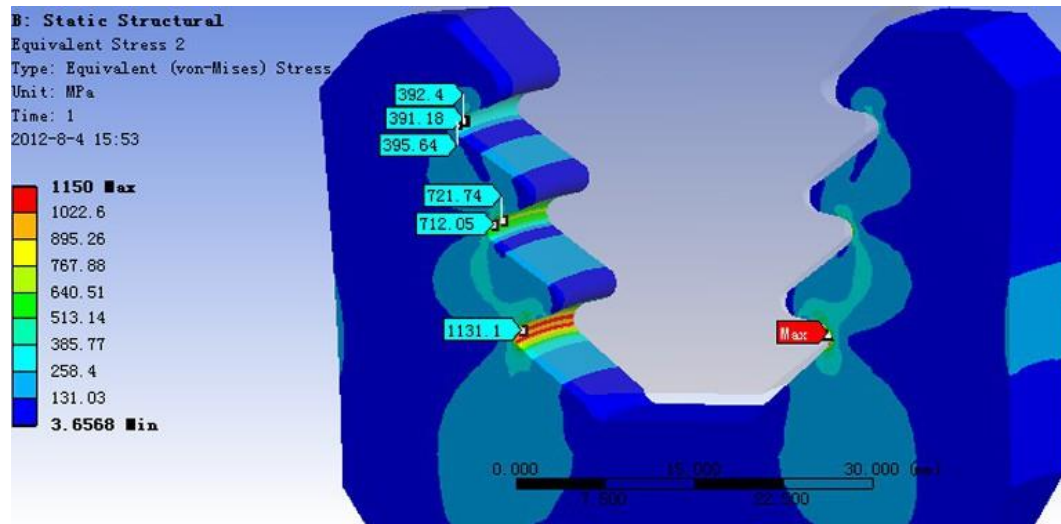


Figure 5. Rim stress distribution cloud map

3.2. Optimized Design

3.2.1. Blade Rim Improvement Ideas. In order to reduce the stress of this section, it is possible to reduce the force, the bending moment and the area of the stressed area. The method of increasing the area is not feasible due to the limitation of the structural size of the through-flow portion. Therefore, the maximum stress of the rim can only be reduced from the perspective of reducing the rim force and bending moment. Due to structural constraints, the leaf crown and the leaf type cannot be modified, but the centrifugal force can be reduced by reducing the width of the blade root and reducing the weight of the blade. The improved blade root and rim structure is shown in Figure 7.

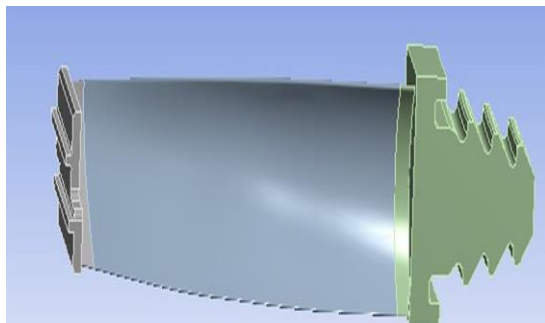


Figure 6. Leaf root with shoulder

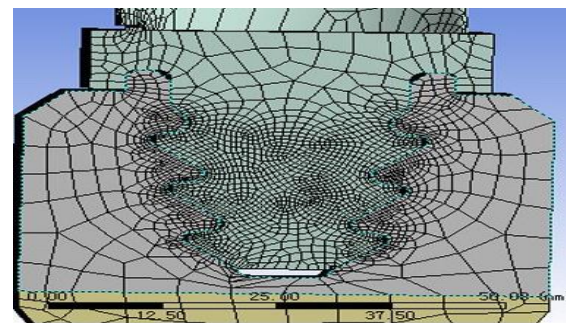


Figure 7. Partial enlarged view of the blade root and rim grid

3.2.2. Analysis of Static Strength of Blade Root Rim after Optimization. Consistent with the pre-optimization analysis method, the mesh of the leaf root and the rim part of the focus is refined, and the rest of the mesh is thicker. The number of finite element units is 95658, the number of nodes is 346537, where the number of blade units is 77674, the number of nodes is 263096, the number of roulette units is 17984, which is shown in Figure 7.

Table 1 shows the comparison of the maximum equivalent stress of the blade root and the rim before and after the improvement. The comparative analysis of the calculated results shows that the maximum

equivalent stress of the improved rim is 743 MPa, which is about 35% lower than the original designed strength requirement.

Table 1. Maximum stress before and after improvement

material	Von Mises equivalent stress, MPa	Optimized Von Mises equivalent stress, MPa	$\sigma_{0.2}$, MPa	σ_b , MPa
Leaf root	758	460.9	900-980	950
rim	1150	743	760	860

4. Conclusion

This paper introduces the structure of steam turbine blades and analyzes the research status of blade parametric design at home and abroad. Taking the last stage blade of steam turbine as an example, the strength analysis of the tooth root and rim of the last stage blade is carried out. The results show that the original design rim stress exceeds the allowable range of the material. From the perspective of reducing the centrifugal force and bending moment of the blade, the structure optimization of the blade root and the rim structure was carried out. The optimized finite element analysis showed that the toothed root and rim structure with shoulders significantly reduced the rim. The stress increases the safety of the rim and lays the foundation for the flow design of the unit.

Not only that, this paper describes the important role of titanium alloys in the manufacture of steam turbine blades, the application of titanium alloy can greatly reduce the weight of the whole machine, improve the thermoelectric conversion efficiency of the unit, and adapt to the higher temperature, pressure, efficiency of the steam turbine., the trend of long-life development is much more costly for power plants than for one-time inputs. Therefore, titanium alloy blades will have broad application prospects on steam turbines, and it is an important development trend of steam turbine blades in China.

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