Structure Topology Optimization of Brake Pad in Large-megawatt Wind Turbine Brake Considering Thermal-structural Coupling

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Abstract. There always exists severe non-uniform wear of brake pad in large-megawatt wind turbine brake during the braking process, which has the brake pad worn out in advance and even threatens the safety production of wind turbine. The root cause of this phenomenon is the non-uniform deformation caused by thermal-structural coupling effect between brake pad and disc while braking under the conditions of both high speed and heavy load. For this problem, mathematical model of thermal-structural coupling analysis is built. Based on the topology optimization method of Solid Isotropic Microstructures with Penalization, SIMP, structure topology optimization of brake pad is developed considering the deformation caused by thermal-structural coupling effect. The objective function is the minimum flexibility, and the structure topology optimization model of brake pad is established after indirect thermal-structural coupling analysis. Compared with the optimization result considering non-thermal-structural coupling, the conspicuous influence of thermal effect on brake pad wear and deformation is proven as well as the rationality of taking thermal-structural coupling effect as optimization condition. Reconstructed model is built according to the result, meanwhile analysis for verification is carried out with the same working condition. This study provides theoretical foundation for the design of high-speed and heavy-load brake pad. The new structure may provide design reference for improving the stress condition between brake pad and disc, enhancing the use ratio of friction material and increasing the working performance of large-megawatt wind turbine brake.

1. Introduction

With the gradual consumption of traditional energy, wind energy and other renewable energy resources have become vigorously developed energy resources all over the world. Wind turbines are developing to larger capacity level. Large-megawatt wind turbine has high rotational speed and heavy load. It has been a key point to study on braking system of the wind turbine. Wind turbine brake works without people to ensure the safety production during a long time [1]. Brake pads are not rigid body and thermal insulation, meanwhile a large amount of heat is generated by the effect of friction, which reduces the coefficient of sliding friction in friction pair, and has an influence on the efficiency of braking, ultimately results in the abnormal operation. With the combined action of the brake force, the friction resistance and the heat, the brake pad comes to deformation. The actual contact area is reduced, which causes serious non uniform wear of brake pads and further reduces the braking performance and friction material utilization. The working condition of the brake pad is analyzed in this paper. After the simplification of brake pad model, the thermal-structural coupling analysis is been finished, whose result is seen as a target to continue with structure topology optimization of the brake pad using SIMP method. According to the topological result and the machinability of the structure, the reliability of
rebuild model is verified in the thermal-structural coupling analysis. Compared with former structure, advantages of new structure are shown.

2. Brake working condition analysis and its modeling

2.1. Brake condition analysis
In the braking process, the brake force makes the brake pad contact with the brake disc. Therefore, there is a brake force with certain size and direction perpendicular to the contact surface in central position on the top of brake pad. In this process, there is a friction resistant with direction opposite to the rotation speed. Besides, in order to limit the relative motion of the brake pad, constraints should be imposed on the model. In order to ensure the normal operation of the brake pad, the movement of the contact surface between the brake pad and brake disc needs to be constrained. The brake pad has been designed groove on both left and right sides. In addition, it is assumed that the contact style between the brake pad and brake disc is surface to surface, so the free degree of the bottom surface on the brake pad is required constraints.

2.2. Establishment of brake pad model
After the model is simplified, there are 6780 elements and 8646 nodes after meshing. Material of large-megawatt wind turbine brake is copper based powder metallurgy, and its material properties are shown in Table 1. The circular area of the model is applied with brake force, and based on the coulomb friction law, the lower surface is applies with friction force. Constrain X, Y directions on both sides in the groove, which can limit the traverse between the brake pad and the brake disc. Constrain Z direction at the bottom surface of the brake pad can restrain the contact form. between the brake pad and the brake disc contact surface. The established model is shown in Figure 1.

| Density (kg/m³) | Elasticity Modulus (MPa) | Thermal Conductivity W/(m·°C) | Specific Heat Capacity J/(kg·°C) | Poisson's Ratio | Linear Expansion Coefficient /°C | Coefficient of Sliding Friction |
|----------------|---------------------------|-------------------------------|-------------------------------|----------------|-------------------------------|-------------------------------|
| 5250           | 5200                      | 30                            | 550                           | 0.3            | 1.5 × 10⁻¹¹                   | 0.3                           |

Figure 1. The model of wind turbine brake pad.

3. Thermal-structural Coupling Analysis
Through the heat transfer calculation, relevant thermal conditions are developed, and the thermal-structural coupling analysis of brake pad is carried out with ANSYS finite element analysis software, which obtains the strain and stress contours as shown in Figure 2 and Figure 3 respectively. From the strain contour in Figure 2, the maximum deformation occurs in the top surface of the brake pad, in other words, the maximum deformation locates in the brake under the positive pressure. This is because large-megawatt wind turbine brake needs larger brake force to meet the requirement of
braking, but the action area of brake force on the top surface is very small, which makes the stress concentration, and further causes large strain in this area, as shown in Figure 3. In addition, in Figure 2, there is large strain in the bottom left area of the brake pad, which corresponds to the inlet side of the friction resistance in Figure 1. Due to the direction of the friction and braking pressure, the effect of resultant makes that the brake has the trend of extrusion to the export side, which means the brake pad becomes a more flexible deforming cantilever beam. The deformation makes the brake pad easier to separate from the brake disc, which decreases the braking performance directly. In the stress contour, as shown in Figure 3, it is easily to find the extrusion trend. There is obvious stress concentration on the export side. In order to improve the issues of the existed deformation and stress concentration of the brake pad with actual working condition, decrease the non-uniform wear and improve the braking performance as well as the use ratio of friction material, structure topology optimization considering thermal-structural coupling of the brake pad is developed to optimize the distribution of friction blocks on the brake pad.

4. Structure Topology Optimization

Topology optimization is a mathematical method to optimize the distribution of materials in a certain region with given loads, constraints and performance indexes [5]. At present, the continuum topology optimization method includes variable density method, homogenization method, etc. [6-8]. Relationship between the material property and density is defined in the variable density method, which means that the density of element is the design variable.[9-11] With the advantages of easy program and high efficiency, this method is widely used in the continuum topology optimization which chooses stress and strain as responses.[12] The design variable of topology optimization method based on Solid Isotropic Microstructures with Penalization is the density of every element in the design area, which changes between 0 to 1 continuously.

Based on Solid Isotropic Microstructures with Penalization method and combined with the result of thermal-structural coupling analysis, structure of brake pad is optimized in this paper. Firstly, the actual working condition is determined, and the finite element model is established with the condition of constraints and loads. Secondly, the thermal-structural coupling analysis is developed. The performance of brake pad is analyzed according to the analysis result, which is also seen as the boundary conditions of the optimization. Thirdly, the mathemtic model is established to carry out the topology optimization. Considering the processing technology of the brake pad and the machinability of the structure, the result of topology optimization is reconstructed. To ensure the new structure meeting the requirement of the optimization, the thermal-structural coupling analysis is developed again. If it meets the requirement, the analysis is over, if not, it should be returned to modify the model.

4.1. Result of Structure Topology Optimization
Based on the result of the thermal-structural coupling analysis, the value of strain on every node is taken out, which is imported to the model of structure topology optimization as imposed displacement to simulate the actual working condition of the brake pad. The design variable is the density of every element. The boundary conditions are (1) the strain of area with braking force on the top surface of the brake pad should be no more than 0.05mm, (2) the volume fraction of the brake pad should be between 50% to 80% to increase the use ratio of the friction material. Considering the effect of thermal-structural coupling, the structure topology optimization of wind turbine brake pad is shown in Figure 4. Because of the thermal effect, the density of most elements is about 0.35 in Figure 4(a). Choose the threshold value as 0.35 to control the density with [0.35,1], which is shown in Figure 4(b).

![Figure 4. Structure topology optimization result density contour](image)

(a) Density form 0 to 1 (b) Density form 0.35 to 1

4.2. Structure Topology Optimization Result Analysis

Topology model of brake pad can be seen in Figure 4(b) obviously. Materials on two sides of direction Y are deleted, and most of the materials are stored around the two grooves. Materials in the middle of the brake pad near the entry of the friction are deleted, but there is an obvious bulge in the center of the brake pad. Corresponding to the position of maximum strain in Figure 3, few materials are deleted in the center on the top surface of the brake pad in Figure 4(b). The maximum contact stress does not appear on the surface, but the subsurface below near the surface. To meet the requirement of manufacturing and the contact condition of braking process, materials here should be retained. To remit the stress concentration caused by braking pressure and friction during braking, pad width of the entry of friction is smaller than that of the exit. Compared with the result of structure topology optimization only considering static condition in Reference 13, there is an obvious change that is the interspace on the bottom of the brake pad. Considering the thermal effect, only the uniform change of temperature, can the brake pad deform and wear uniformly. The interspace can make the heat transfer more fluently and decrease the materials store in the exit of friction. To meet the stiffness requirement of the brake pad in the center, two bulges are designed on each side of the brake pad on the bottom where contacts with the brake disc.

4.3. Reconstruction of the Brake Pad and Result Verification

4.3.1. Reconstruction of the Brake Pad. The final structure of wind turbine brake pad can be reconstructed based on the topological model. The machinability of the reconstructed structure should be concerned. As the large-megawatt wind turbine brake pad is made in copper based powder metallurgy material through sintering and pressing with high temperature, and the corresponding moulds will be designed according to the structure of brake pad, a principle taking manufacturing of moulds conveniently should be considered, the final structure of brake pad is shown in Figure 5.
4.3.2. **Verification of the Reconstructed Structure.** The stress and strain contours shown in Figure 6 are the results of verification finite element analysis of the reconstructed structure. The maximum strain of the brake pad is 0.045 mm, which is less than 0.05 mm and meets the requirement of the optimization object.

![Figure 6. Reconstruction model validation result contour](image)

Compared with the result of thermal-structural coupling analysis of the brake pad, the degree of deformation of the brake pad decreases a little. In the strain contour of verification analysis shown in Figure 6(a), there is only a little or no deformation on both entry and exit sides of the friction, especially the entry side, which means the topology optimization result is good to the stability of the braking process and has inhibiting effect on the non-uniform wear of the brake pad. In the stress contour shown in Figure 6(b), the maximum stress appears in the middle of the brake pad, the value of stress of most materials on both entry and exit sides is about 0.02 MPa, which distributes evenly. Compared with the stress contour shown in Figure 4, because of the effect of thermal-structural coupling, stress in the area of brake force and the exit side of the friction is higher than other areas, which means the optimized stress distribution is much better than the origin one. Besides, both the mass and volume of the brake pad decrease, which increases the use ratio of the friction materials indirectly.

5. **Conclusions**

For the issues of severe non-uniform wear of brake pad in large-megawatt wind turbine brake during the braking process, the indirect thermal-structural coupling method is used in this paper to develop the stiffness condition of the brake pad considering thermal-structural coupling. The analysis result is imposed as equivalent displacement in the optimization model, with the topology optimization method of Solid Isotropic Material with Penalization, the maximum stiffness of the brake pad is set as the optimization object to meet the requirement of the thermal-structural coupling working condition, and the distribution of the friction block on the brake pad is designed. The volume and mass of the new structure is less than the origin one, which remits the non-uniform wear of the brake pad and increases the use ratio of the copper based powder metallurgy friction material. The verification finite element analysis of the optimized structure under the same working condition shows the advantages of working performance of optimized structure in the actual working condition.

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