Optimization of Curved Fir-Tree Root of Steam Turbine Using Computer Aided Optimization and Finite Element Analysis

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Abstract: This paper is concerned with optimization of the design of a turbine blade curved fir-tree root and rim by integrating a knowledge of computer aided optimization (CAO) and finite element analysis (FEA). The optimization software Isight and FEA software Abaqus are applied in an effort to optimize the shape of the curved fir-tree root of a given turbine blade. During this process, root profile from axial perspective is fixed, while attention is devoted to assess the effect of geometrical feature from the radial perspective. Several critical geometrical features such as the radius of root centerline, (x, y) coordinate of center point of the centerline, and distances from blade center to leading and trailing edge of the platform, are taken as design variables and the maximum equivalent stress of root and rim as objective function. Two optimization algorithms are employed in this paper. Compared with the original structure, the position of the maximum equivalent stress after optimization hardly changes while the maximum equivalent stress of root is reduced significantly, resulting in better operation reliability of turbine blade. A product model from Shanghai Electric (Group) Corporation (SEC) is used as a preliminary design in the optimization.

Key Words: Steam turbine blade, Curved root, Finite element analysis, Multi-Island Genetic Algorithm, Downhill Simplex

1. Introduction

Last stage long blade is a core part of steam turbine, it directly influences the performance of steam turbine and represents the most advanced level of steam turbine technology. During the operation of steam turbine, blade root suffers from huge centrifugal force generated by all the rotating blade. Take a 3000rpm last stage blade for example, the centrifugal force root bears will be as large as the weight of a train. As a result, root design is of great importance in blade development. Generally, fir-tree root is a root style which is widely used in last stage blade. Compared to Tee root, fir-tree root has more pairs of contacts, resulting in smaller stress on each contact pair. Curved fir-tree root, as an improved version, is more advanced and has obvious advantages. Compared to traditional side entry straight fir-tree root, curved root has larger contact areas, thereby has smaller stress, loading the same centrifugal force. With the development of modern steam turbine, there is a need to make longer blades, nowadays long blades can be longer than 1200mm, and even longer. With the ascending problems in root design process, it is quite urgent to study the shape optimization of blade root.

There is plenty of research that concerns the optimization of steam turbine blade root at present. The urgent optimization issues to tackle involve static stress, strain and durability. Most of these issues are strongly nonlinear and multi-peak problems. Among the numerous optimization algorithms, Genetic Algorithm plays a representative role of non-classical optimization algorithm, which has received some attention for these problems recently. It has so many advantages as simple currency, strong robustness and parallel processing possibility, which can easily overcome the limitation of traditional optimization. But there are still some practical disadvantages, such as poor local search, premature convergence, slow convergence, etc. (Hu, 2014). Thus, an improvement is made and Multi-Island Genetic Algorithm is employed in this paper. Although

MIGA has advantages that TGA does not have, there is still one disadvantage it cannot overcome. Good global search capability calls for high computational cost, resulting in this optimization algorithm be not well-suited for long running problems. For some engineering optimization problems like in this paper, fast design improvement is much more important than finding a global optimum solution. Thereby, another optimization algorithm Downhill Simplex is also employed in this paper. The results of both optimization algorithms are compared and analyzed respectively.

Blade root shape optimization is a topic which is studied by a large number of scholars (Zhang, 2012; Wu, 2012). According to JS Rao and B Kumar's paper (J.S. Rao, 2012), a turbine blade with a curved entry root shape is optimized to achieve minimum plastic strain. Three different DOE methods (Latin Hypercube, Hammersley and Box-Behnken) are chosen in this optimization study. In W Song's paper (Song, 2002), intelligent CAD system and finite element method are employed to realize the automation and optimization of the design of a turbine blade fir-tree root. During the optimization, OPTIONS software package is employed and Genetic Algorithm is chosen. However, past research mainly studied the optimization of root profile from the axial perspective, there is few research on the shape optimization of curved root from the radial perspective. According to practical experience, parameters in this perspective influences the stress distribution significantly. In this paper, root profile from axial perspective is fixed, while attention is devoted to examining the effect geometry features from the radial perspective. During this process, optimization software Isight is employed to manage the data flow and control the optimization parameters, Finite element software Abaqus is employed to carry on finite element analysis of blade-groove model. Several geometric parameters are chosen and optimization objective is to minimize the max Mises stress on blade root.

2. Problem configuration

The optimization of blade root shape essentially belongs to constrained optimization problems. With highly nonlinear characteristics as geometry discontinuity and contact nonlinearity, this problem often has a large number of local optimums. Typical blade-groove contact model includes a blade, corresponding part of groove and the contact of them.

The optimization proceeding of the problem is shown in Figure 1. As the decrease of max Mises stress means the reliability of turbine operation, the max Mises stress of both root and groove is an important indicator, especially for last stage blades. Once the root profile from axial perspective is fixed, the stress distribution is mainly influenced by geometry features from radial perspective, such as radius of root centerline, (x, y) coordinate of center point of the centerline, and distances from blade center to leading and trailing edge of the platform. Furthermore, According to present experience, stress of groove is usually smaller than that of corresponding root, thereby only the max Mises stress of root is taken as the optimal objective, for the purpose of reducing the complexity of this problem.

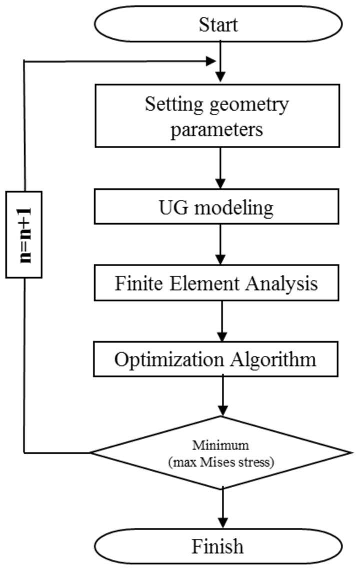


Figure 1. Optimization proceeding of the problem

3. Integrated optimization based on MIGA & Downhill Simplex

In this paper, two optimization algorithms are employed to carry on optimization of root shape. The global optimization is mainly for specifying the standard values of geometry parameters of root from radial perspective under the circumstance of minimum max Mises stress on root, while another algorithm is mainly for quick improvement of blade root design. The corresponding two algorithms are Multi-Island Genetic Algorithm and Downhill Simplex, specifically.

In the Multi-Island Genetic Algorithm (MIGA), like other genetic algorithms, each design point is perceived as an individual with a certain value of fitness based on the value of the objective function and constraint penalty. An individual with a better value of the objective function and penalty has a higher fitness value. Each population presents a set of design points, which is altered by genetic operations as follows: selection, crossover and mutation. In the selection process, a new population of individuals is selected according to the survival of the fittest theory; in the crossover operation, two individuals are crossed at 2 points and the genes between those points are swapped in the two chromosomes resulting in two new individuals. In the mutation operation, similar to the biological mutation, a randomly selected gene is changed to further increase the variability of population and avoid stagnation in the evolution process. Meanwhile, the best individuals called elites are preserved without alternation, to make sure that the best genetic material is carried over to child population (Isight Users Manual).

The main feature of Multi-Island Genetic Algorithm that distinguishes it from traditional genetic algorithms is the fact that each population of individuals is divided into several sub-populations called "islands". All traditional genetic operations are performed separately on each sub-population. Some individuals are then selected from each island and migrated to different islands periodically. This operation is called "migration" (Meng, 2010). Two parameters control the migration process: migration interval which is the number of generations between each migration, and migration rate which is the percentage of individuals migrated from each island at the time of migration (Chen, 2008).

The Downhill Simplex method is a geometrically intuitive algorithm. A simplex is defined as a body in n dimensions consisting of n+1 vertices. Specifying the location of each vertex fully defines the simplex. This method requires that you define an initial simplex by specifying N + 1 starting points. That is to say, you must judge the best location from which to start. Starting with the initial simplex defined by the points, the downhill simplex method performs a series of reflections. A reflection moves from a point on the simplex through the opposite face of the simplex to a point where the function *f* is smaller. The configuration of the reflections conserves the volume of the simplex, which maintains the non-degeneracy of the simplex. However, sometimes expansion will occur during reflection to make convergency faster. Conversely, shrinking of simplex can also occur, allowing it to settle into a minimum or pass through a small opening like the neck of an hourglass (Isight Users Manual).

This method has the highest probability of finding the global minimum when it is started with big initial steps. However, for complex hyper-dimensional topographies, the method can break down. Besides, the result of this method can vary due to different initial geometry. Thereby, selection of starting point is quite important when employing this method.

As we can see from the comparison above, Multi-Island Genetic Algorithm is a method for global optimization, which is not well suited for long running problems, but can find a global optimum solution robustly; while Downhill Simplex is an exploratory technique method for quick design improvement, which is well suited for long running problems, but may result in the poor local search. Optimization parameters for each algorithm are shown in Table 1 and Table 2, respectively.

Table 1. Optimization parameters of Downhill Simplex

Option	Value
Initial Simplex Size	0.1
Max Iteration	100
Max Failed Runs	5
Failed Run Penalty	1.0E30
Failed Run Objective	1.0E30

Table 2. Optimization parameters of MIGA

Option	Value
Sub-Population Size	10
Number of Islands	10
Number of Generations	10
Rate of Crossover	1.0
Rate of Mutation	0.01
Rate of Migration	0.01
Interval of Migration	5
Elite Size	1
Rel Tournament Size	0.5
Penalty Base	0.0
Penalty Multiplier	1000.0
Penalty Exponent	2
Default Variable Bound (Abs Val)	1000.0
Max Failed Runs	5

Failed Run Penalty Value	1.0E30
Failed Run Objective Value	1.0E30

4. Employing the derived approach for a model problem

4.1 Optimization strategy

The optimization approach introduced in this paper is employed for a product model from SEC. Figure 2 shows the base design. The product model chosen is a free standing blade to get rid of the difficulty in assembly. Besides, to make model assembly and mesh generation easier, transition arc of middle part is simplified. Figure 3 shows the view from radial perspective, in which main parameters are labeled. The parameters have fixed values except three design variables: Rin, LengthLeft and RootOffset. In this model, shape of airfoil is fixed, while shape of groove changes with the corresponding changes of the shape of root. To make sure that the platform can cover the base section of airfoil, range of three design parameters has some limitations as listed in Table 3.

Figure 2. Base design

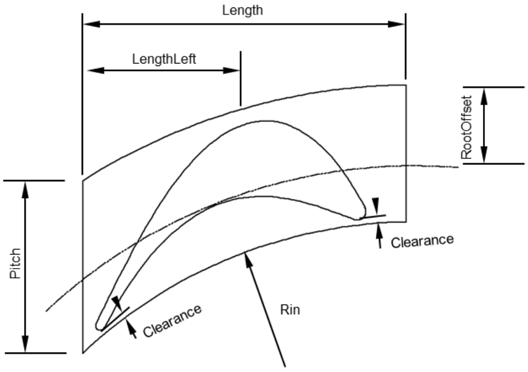


Figure 2. Radial view of platform and root

Table 3. Range of design variables

Design Variable	Initial	Low bound	Up bound
Rin (mm)	300	300	600
LengthLeft (mm)	100	100	115

RootOffset (mm)	50	35	50

During the optimization, the Downhill Simplex algorithm is first employed to achieve a fast improvement, then a global optimization is carried on employing Multi-Island Genetic Algorithm.

4.2 Integration of optimization algorithms and finite element analysis

A commercial optimization software would be preferable for integrating optimization algorithms and finite element analysis. Isight is such an optimization software combining industrial optimization design and automatic analysis. The integration of Isight and other software does not have a uniform standard and method. So it is important to further study the interface to connect Isight and FEA software. In this paper, interface is developed between Isight and UG /Abaqus. In general, the integration of Isight and UG/Abaqus requires the definition of data transfer, such as importing, exporting and data processing. Figure 4 shows a typical integrated platform, which can monitor the whole optimization process and accomplish the optimization design. The Optimization1 module controls the optimization algorithm and value of design variables, GoUG module updates geometry models based on the received design variables, and GoAbaqus module is in charge of pre-processing, solving, and post-processing, these functions are realized by secondary development of Abaqus using Python language. Then the output of module GoAbaqus is transferred to module DataExchanger, which picks the max Mises stress and passes it to module Optimization as an objective function.

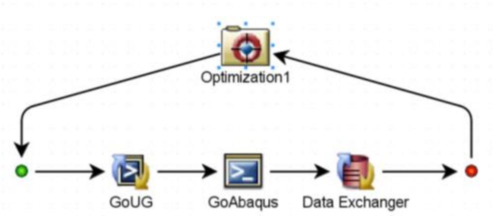


Figure 4. Integrated platform of Isight and UG/Abaqus

4.3 Finite Element Model

To model the real operation condition of the blade, a one sector model is considered and the constraint of cyclic symmetry is applied. All three degrees of freedom of the bottom face of groove is fixed. To make it easy to assembly, the part of airfoil is tied to up face of the middle part. Then, general contact is set on the corresponding areas of root and groove. All the boundary conditions mentioned above are illustrated in Figure 5. At last, rotational body force is applied on the whole model.

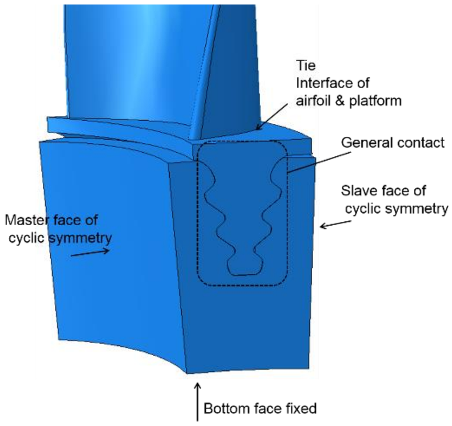


Figure 5. Boundary conditions illustration

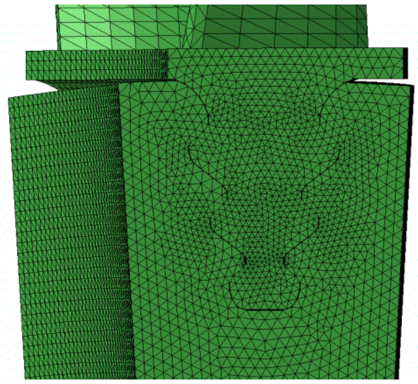


Figure 6. Mesh modeling

In general, finite element analysis is computational expensive, there should be a balance between accuracy of result and computational cost, especially time consumption. So compromise is made by adjusting the density of mesh. In such a model, mesh is really rough, the element size and mesh quality can be seen from Figure 6. Although mesh quality is relatively low, the result of analysis can tell the difference between the original design and the design after optimization. Mesh parameters are listed in Table 4.

Table 4. Mesh parameters

Position	Element size	Element type
Root	4	Linear tetrahedral element (C3D4)
Groove	4	
Airfoil	10	
Mesh quantity (Base Design)	409376 elements, 80202 nodes	

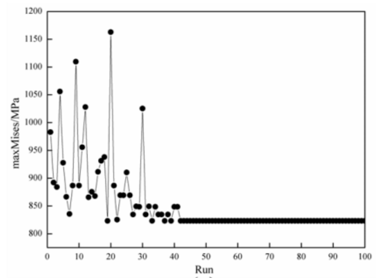
Finite element software Abaqus supports batch running of the analysis and this allows the analysis to be embedded into the overall optimization loop. Thereby, the whole process from importing geometry, assembling, meshing, setting boundary constraints, applying loads and post data processing are finished automatically by calling a script. During which, the geometry file is generated by module GoUG automatically, and the output data of module GoAbaqus is transferred to module DataExchanger.

4.4 Optimization Results

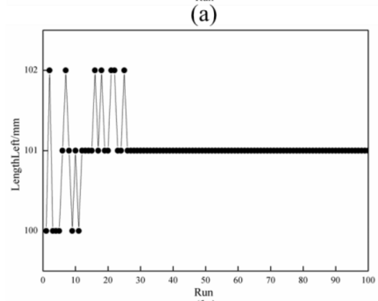
Two optimization algorithms are applied in this optimization task, so the results of them are compared and analyzed respectively.

4.4.1 Optimization by Downhill Simplex

Figure 7(a) illustrates the history of max Mises stress changes with optimization loops. Predefined loop number is 500, but the optimization finished after 200 loops. The max Mises stress of original design is as large as 982MPa, while it changed to 823MPa, with a reduction of 159MPa, 16.2% relatively, which is really significant. Figure 7(b) (c) (d) illustrates the history of three design variables during optimization, from which we can see there is no obvious regularity of LengthLeft, nor is RootOffset before convergence. However, the variable Rin tends to convergent after 40 loops. Obviously, the optimum solution achieved is a local search result, which is far away from the global optimum solution. However, this solution is easily reached, with a significant reduction in max Mises stress, which is enough for an engineering problem. What’s more important, the optimum solution is reached in about 40 loops, spending 13.3hours.



(a)



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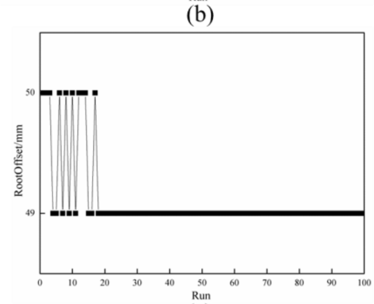
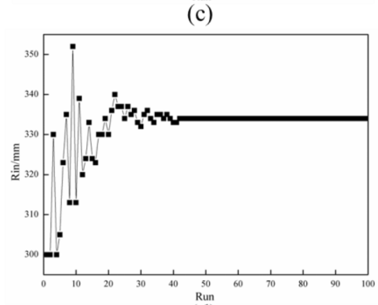


(c)



(d)

Figure 7. History of parameters during Downhill Simplex process

4.4.2 Optimization by MIGA

Due to time and computational resource limitation, the whole optimization process by MIGA is not finished up to now. However, the result so far is worth discussing. Figure 8(a) illustrate the history of max Mises stress changes with optimization loops, it changes from the original 982MPa to 580MPa, with a reduction of 402MPa, 41.2% relatively. Figure 8(b) (c) (d) illustrates the history of three design variables during optimization, which is obviously different from that of Downhill Simplex. The variable LengthLeft tends to converge around the value of 105, while the variable RootOffset tends to converge around the value of 43. However, the variable Rin does not show any obvious convergency after such loops. The optimization of MIGA is time and computational costly. The result so far is reached in 430 loops, spending 143.3 hours.

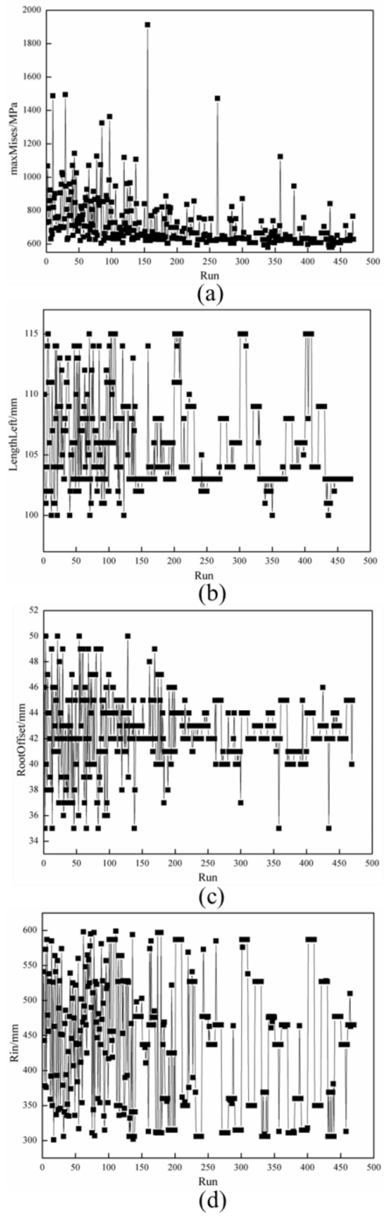


Figure 8. History of parameters during MIGA process

Table 5 shows the comparison between the results of Downhill Simplex and MIGA. Downhill Simplex is well-suited for long-running optimization problems, while MIGA is not well-suited for that. Downhill Simplex takes shorter time to accomplish a fast design improvement for engineering development, while MIGA takes more time and computational resource to find a global optimum solution, which is suitable for research purpose.

Table 5. Result comparison between Downhill Simplex & MIGA

	Downhill Simplex	MIGA
Cpus	16	16
Loops	40	430
Time consumed	13.3hours	143.3hours
Optimum solution	823MPa	580MPa
Percentage of reduction	16.2%	41.2%

5. Optimization design verification

It has been shown from previous preliminary optimization work that it is possible to reduce max Mises stress significantly by adjusting geometry parameters from radial perspective. However, the mesh shown in the previous chapters is really rough. To find out the real difference between designs before and after optimization, a fine mesh model is employed and precise finite element analysis is carried on in this chapter.

Three cases are studied: the original prototype, the optimized model after Downhill Simplex optimization, and the optimized model after Multi-Island Genetic Algorithm optimization. The geometry parameters of these models are listed in Table 6.

Table 6. Geometry parameters of verification models

	LengthLeft (mm)	Rin (mm)	RootOffset (mm)
Original prototype	100	300	50
Downhill Simplex	101	334	49
MIGA	101	306	42

Finite element analysis is carried on using finite element software Abaqus, as well. Boundary conditions and load are the same as illustrated above. Fine mesh is generated by pre-process software Ansa, and the mesh is illustrated in Figure 9. Airfoil, middle part, root and groove are all meshed by structured mesh, with the element type of C3D8I (8 node linear incompatible element). Mesh near the contact surface is especially refined both to speed the calculation, and to make result more accurate.

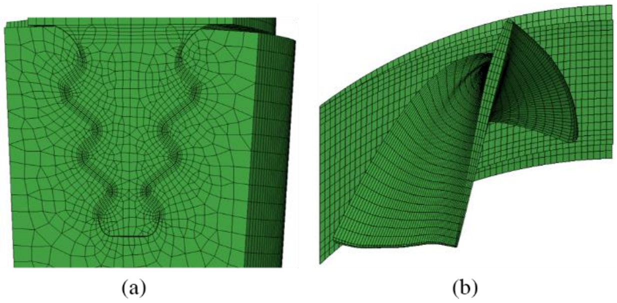


Fig 9. Fine mesh for design verification

Mises stress contours of root are illustrated in Figure 10, Figure 11, and Figure12, respectively. The up contour in each figure shows the stress distribution in convex side, while the down contour shows the stress distribution in concave side. In the case of original prototype, max Mises stress of root is as big as 924MPa, exceeding the yield limit of blade material. What's more, in this case, stress in the convex side is much bigger than that in the concave side, which means the load distribution is non-uniform. In the case of Downhill Simplex, max Mises stress of root is 876MPa, which is a bit smaller than that of original design. Such a stress reduction can easily satisfy the demand of engineering application. However, the stress difference between convex and concave side is still large. In the case of Multi-Island Genetic Algorithm, max Mises stress of root is 645MPa, which is much smaller than that of the other two cases. Besides, seen from the color, values of max stress of convex and concave side are close, which means the load distribution on the root is more reasonable in this case. The results are sum up in Table 7.

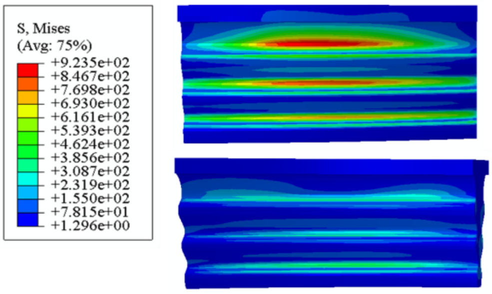


Fig 10. Mises stress contour of root (Original prototype case)

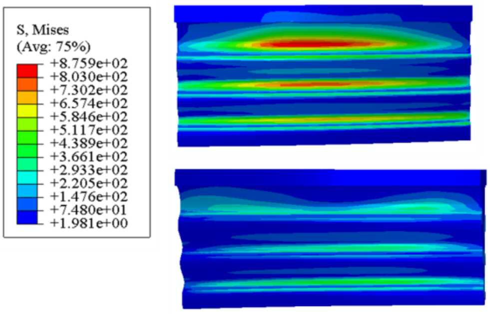


Fig 11. Mises stress contour of root (Downhill Simplex case)

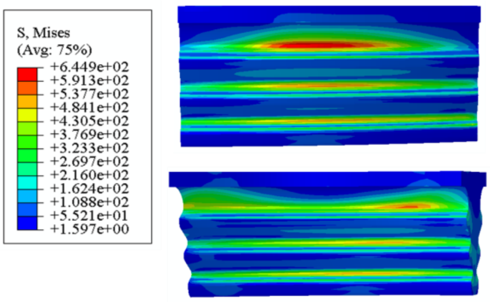


Fig 12. Mises stress contour of root (MIGA case)

Table 7. Verification result summation

	Original prototype	Downhill Simplex	MIGA
Max Mises stress (MPa)	924	876	645
Stress reduction (MPa)	0	48	279

Stress reduction rate	0	5.19%	32.19%

6. Conclusions

According to the result of optimization by MIGA, max Mises stress is most sensitive to parameter RootOffset. The process tends to converge after 430 loops, but final convergency is not reached due to time limitation. The optimum solution (maybe the global optimum solution), max Mises stress=645MPa, can be reached when LengthLeft =101, Rin =306 and RootOffset =42, according to the FEA result of verification.

According to the result of optimization by Downhill Simplex, max Mises stress does not show any obvious sensitivity to any single parameter. But the result is converge to 823MPa, when LengthLeft =101, Rin =334 and RootOffset =49, according to the FEA result of verification.

The max Mises stress is reduced after optimization significantly, proving that the technical route of the optimization is reasonable. The algorithm of Downhill Simplex is suitable for long-running problems. In this paper, it accomplishes a quick improvement in design within 13.3 hours, with a result significant for engineering application. The algorithm of Multi-Island Genetic Algorithm is able to find the global optimum solution robustly, which is much better than that of Downhill Simplex. However, the MIGA method requires more time and computational resource. In simple engineering problems, the time of several hundred hours is acceptable, while for complex problems, there must be a compromise between efficiency and accuracy.

7. References

[1] SONG Wenbin, Andy Keane, Janet Rees, Atul Bhaskar, Steven Bagnall. Turbine Blade Fir-tree Root Design Optimisation Using Intelligent CAD and Finite Element Analysis [J]. Computers & Structures. 2002, 80: 1853-1867;

[2] KONG Haipeng, LI Ni, SHEN Yuzhong. Adaptive Double Chain Quantum Genetic Algorithm for Constrained Optimization Problems [J]. Chinese Journal of Aeronautics. 2015, 28(1): 214-228;

[3] GAO Xiaoxia, YANG Hongxing, LU Lin, Prentice Koo. Wind Turbine Layout Optimization Using Multi-population Genetic Algorithm and A Case Study in Hong Kong Offshore [J]. Journal of Wind Engineering and Industrial Aerodynamics. 2015, 139: 89-99;

[4] HU Xingzhi, CHEN Xiaoqian, ZHAO Yong, YAO Wen. Optimization Design of Satellite Separation Systems Based on Multi-Island Genetic Algorithm [J]. Advances in Space Research. 2014, 53: 870-876;

[5] CHEN Hong, Ooka Ryozo, Kato Shinsuke. Study on Optimum Design Method for Pleasant Outdoor Thermal Environment using Genetic Algorithms and Coupled Simulation of Convection, Radiation and Conduction [J]. Building and Environment. 2008, 43(1): 18-30;

[6] MENG Xiangzhong, Ni Jinping, ZHU Yanbo. Research of Active Vibration Control Optimal Disposition Based on MIGA and NSGA-II [C]. Sixth International Conference on Natural Computation, Yantai, China, 2010;

[7] J.S. Rao, B. Kumar. 3D Blade root shape optimization [C]. 10th International Conference on Vibrations in Rotating Machinery, 2012, 173-188;

[8] WANG Mingfang, WANG Mei, TAN Junshan, Application of MIGA to Optimal Disposition of Sensors in Active Vibration Control [J]. Journal of Vibration, Measurement & Diagnosis. 2008,28(1):62-65,79;

[9] ZHANG Minghui, ZHANG Di, XIE Yonghui. Design Optimization of Fir-tree Root and Rim for Control Stage Blades Considering 3D Thermo-elastic Contact Problems [J]. Journal of Chinese Society of Power Engineering. 2012,32[7]:501-507,516;

[10] WU Jun, ZHANG Di, MA Dandan, ZHANG Minghui, XIE Yonghui. Optimization for Turbine Blade with Fir-tree Root and Rim by Three-Dimensional Contact Finite Element Method [J]. Journal of Xi’an Jiaotong University. 2012,46(5):25-31;

[11] Abaqus Users Manual, Version 6.14, Dassault Systémes Simulia Corp., Providence, RI;
[12] Isight Users Manual, Dassault Systémes Simulia Corp., Providence, RI.