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MULTIDISCIPLINARY OPTIMIZATION TECHNOLOGY RESEARCH ON TYPICAL TURBINE ASSEMBLY STRUCTURE

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ABSTRACT

A multidisciplinary design optimization (MDO) method for turbine mortise assembly structure is presented. This method takes tenon and mortise as a whole to carry on the design optimization. With the adoption of Design of Experiment (DOE) method and Collaborative Optimization (CO) Strategy, this method has realized the coupling parallel optimization of the mortise assembly structure. To verify the effectiveness of the proposed method a typical fir-tree mortise structure design optimization is provided as an example. The results show that the mass and Von Mises Stress of the mortise assembly structure were reduced remarkably, which means that the proposed method has a significant role in enhancing structural performance.

Keywords: Mortise structure, Collaborative Optimization, Multidisciplinary Design Optimization, Design of Experiment.

INTRODUCTION

Turbine blade tenon and turbine disk mortise assembly structure (referred to mortise structure) is a critical part of the aeroengine turbine assembly structure. On one hand, the mortise structure suffers complex thermal loads and mechanical loads when it works. The rationality of the entire assembly structure design is directly related to the strength, life and reliability of the rotor components, and greatly affects the thrust-weight ratio of the aeroengine[1]. On the other hand, considering the high cost of its processing and long manufacturing cycle, once the initial design is finalized the subsequent design modifications will have greater difficulties. Therefore, it is important to analyse the design features of mortise structure and to establish a complete optimization method.

So far, rich researches in mortise structure design optimization have developed a series of methods. But, domestically, most of the traditional methods usually separate tenon/mortise from the assembly structure rather than as a whole, and consequently, the analysis results are often confined within the scope of their respective disciplines, and eventually fail to reflect the real working condition of the structure[2,3,4,5,6,7]. Thus it is necessary to establish a reasonable overall structure optimization design method for mortise structure. In this paper, a new method is presented for aero engine turbine mortise structure MDO. It is designed to build a two-stage optimization model for mortise structure: a system-level optimization model (main system) and two parallel discipline-level optimization models (subsystem). The CO strategy is used to make sure that the design optimization of the two subsystems is progressed independently. After that, the optimal solution of the system is calculated as a whole under the condition of meeting the coupling between subsystems, thus improving the design problem of mortise structure.

MDO METHOD FOR MORTISE STRUCTURE

Mortise structure involves multiple disciplines such as structural strength, thermal, pneumatic, combustion, vibration, materials and manufacturing processes, etc. It is a typical complex system multidisciplinary variable coupling problem. Figure 1 shows the solving process.

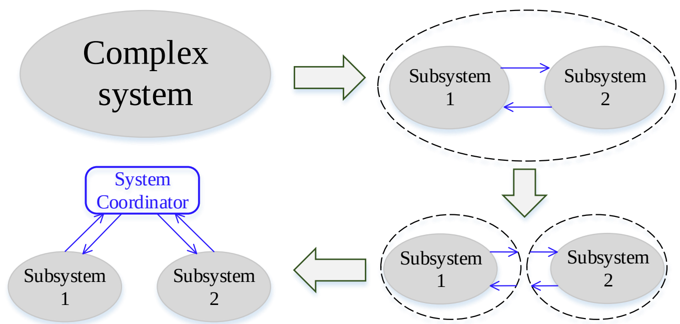


Fig.1: The solving process of multidisciplinary variable coupling problem.

The first step for the complex system MDO process is to divide the complex system into a number of relatively independent subsystems. System coordinator associates subsystems and main system by passing design parameters. It just controls the input and output information and doesn't interference the design optimization process of the subsystems. With the decomposition of the complex system, the system design goal is decomposed into several subsystem design goals, which means that achieving design goals of the subsystems equals achieving the system design goal[8,9,10].

The second step for the complex system MDO is subsystem modeling. Subsystem modeling should be dominated by design requirements of its discipline. Subsystem optimization model is set up on the basis of disciplinary analysis. In principle subsystem modeling should reduce the number of design variables and design constraints as much as possible. In order to improve the efficiency of the overall system design optimization, the usual practice is to simplify the subsystems optimization model by the experience of the expert[11]. Figure 2 shows the basic form of subsystem optimization model.

Subsystem optimization model

Find X_i

Min $f_i(X_i, Y_i)$

s.t. $g_i(X_i, Y_i) \le 0$

$h_i(X_i, Y_i) = 0$

Parameter Meaning

$i=1,\dots,N$	N is the total number of subsystems.
X_i	Design variable vector.
$f_i(X_i, Y_i)$	Objective function.
$g_i(X_i, Y_i)$	Inequality constraint vector.
$h_i(X_i, Y_i)$	Equality constraint vector.

Fig. 2: Subsystem optimization model.

Analyses of the coupling relationship between subsystems are the main contents of the subsystem modeling. Figure 3 shows two simple subsystems to illustrate the coupling relationship between the subsystem optimization models.

Subsystem 1

$$\begin{aligned} &\min.\ F_1(X_1) = W_{f1} * f_1(X_1) \\ &\text{s.t.}\quad g_{1u}(X_1) \le 0,\ u=1,\cdots,m_1 \\ &\qquad h_{1v}(X_1) = 0,\ v=1,\cdots,q_1 \\ &\qquad Y_1 = f_{y1}(X_1) \\ &\qquad X_1 = (X_P, X_{L1}, Y_2)^T \end{aligned}$$

Y_2 ← → Y_1

Subsystem 2

$$\begin{aligned} &\min.\ F_2(X_2) = W_{f2} * f_2(X_2) \\ &\text{s.t.}\quad g_{2u}(X_2) \le 0,\ u=1,\cdots,m_2 \\ &\qquad h_{2v}(X_2) = 0,\ v=1,\cdots,q_2 \\ &\qquad Y_2 = f_{y2}(X_2) \\ &\qquad X_2 = (X_P, X_{L2}, Y_1)^T \end{aligned}$$

Fig. 3: The coupling relationship between two subsystems.

In subsystem 1, X_1 is the set of design variable and it consists of 3 types of design variable, which are public design variables X_P, local design variables X_{L1} and the set of state functions Y_2. Subsystems 2 is similar to subsystem 1. The coupling relationship between the two subsystems mainly depend on X_P and Y_i.

As mentioned before, the design optimization process of each subsystem is relatively independent, so the local design variables X_{Li} is only valid in its subsystem and will not have an impact on other subsystems, while the optimal value of X_P obtained by solving each subsystem will usually be inconsistent. How to make the optimal value of public design variables obtained from different subsystem optimization agree with each other is one of the main subsystem coupling problems.

In subsystem 1 the value of state function Y_1 is related to state function Y_2, and in subsystem 2 the value of state function Y_2 is related to state function Y_1 as well. Y_1 and Y_2 interact, make mutual decision, and constitute the coupling relationship between the two subsystems. Figure 3 shows this relationship.

The third step for the complex system MDO is to select an appropriate algorithm and optimization strategies. Collaborative Optimization algorithm[12] is a kind of double level optimization algorithm, it decomposes the multidisciplinary design optimization problem into discipline-level optimization (subsystem) and system-level optimization, and then it uses the relaxation factor to realize the system level coordination. CO algorithm is mainly suitable for handling the situation in which subsystem variables are much more than the Inter-disciplinary variables, in other words, it is suitable for solving large, loosely coupled systems multidisciplinary collaborative design problems[13,14]. For mortise structure design optimization problems, tenon and mortise are two subsystems of mortise structure, and they are linked by a simple coupling and only have a few public design variables. However, they have a lot of discipline variables (local design variables), which fully meet the condition that subsystems local design variables are significantly more than public design variables. Therefore this research adopts the Collaborative Optimization algorithm.

With respect to the optimization strategy, this paper utilizes Multi-island Genetic Algorithm (MIGA) to explore the entire design space to get the global optimal solution, and then iteratively update and gradually approach the exact global optimal value through the Non-linear Programming by Quadratic Lagrangian (NLPQL).

APPLICATION

The previous section has described the method of mortise structure multidisciplinary coupled variables design optimization, and this section will focus on specific application of these methods to mortise structural design. In this paper, an aero engine fir-tree mortise structure design solution is taken as design conditions. By dividing the mortise structure into two subsystems the optimization model is established. The DOE (Design of Experiment) method is used before executing the optimization, through the subsystem's sensitivity analysis to find out the best influential design variables, and then using the CO solving method, and a combination of MIGA and NLPQL optimization strategy to carry out multidisciplinary design optimization of mortise structure. The basic flow of the method is shown in Figure 4.

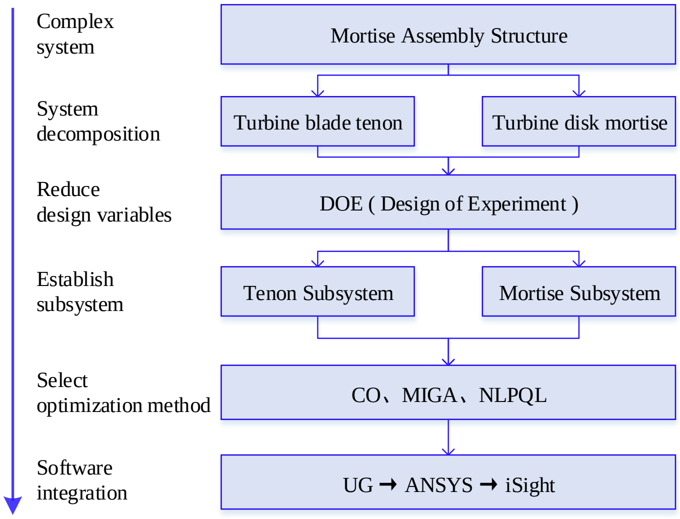


Fig. 4: Basic optimization flow of mortise structural

PARAMETRIC MODELING

UG is the abbreviation of Unigraphics, it is an interactive CAD/CAM system, and in this paper the UG platform is selected as the modeling tool. Under the UG platform, cyclic symmetry method is used to establish a 3D parametric model of the mortise structure as shown in Figure 5-a. Figure 5-b is the simplified model of mortise structure (system), Figure 5-c and 5-d are the subsystems decomposed by the system. Since the mortise and tenon needs assembled together, each tooth pitch must be fully consistent. In the process of mortise subsystem independent optimization, the tooth pitch S_c will get a local optimal solution of S_c', while in the process of tenon subsystem independent optimization, the tooth pitch S_t will also get a local optimal solution of S_t'. S_c' and S_t' inconsistencies resulting coupling problems between the two subsystems. In this research S_c and S_t are chosen as multidisciplinary public design variables of the two subsystems, and then multidisciplinary design optimization of the system is carried out whose local structure has a simple coupling.

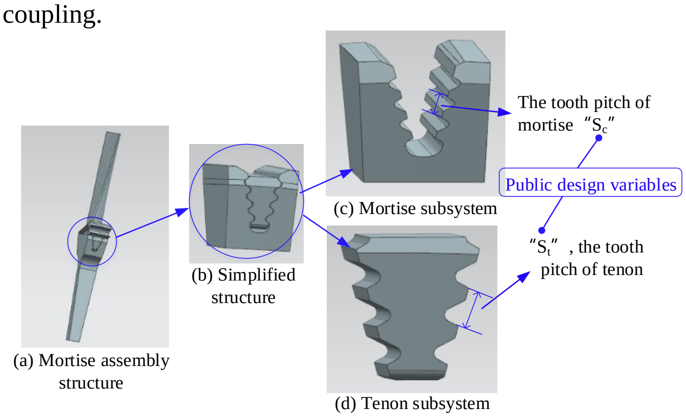


Fig. 5: Parameterized model

The Ni-based superalloy Dz22 is chosen as the material of the blade tenon. This superalloy has a good mechanical behavior under high temperature, and it performs well in thermal fatigue resistance. The Ni-Cr-Fe-based superalloy ZSGH4169 is chosen as the material of the disk mortise. This alloy has high yield strength and good plasticity under 650℃, so it is suitable for the problem discussed in this paper.

DESIGN OF EXPERIMENTAL (DOE)

The mortise assembly structure has a large number of design parameter, and Table 1 shows all design parameters of the mortise structure[15]. If taking all the design parameters as optimal design objects, the complicated calculation process will bring huge computational overhead and is difficult to find the optimal results, even may cause the collapse of the calculation process and eventually lead to the failure in the implementation of the calculation scheme.

Tab.1: Design parameters of the mortise structure

Symbol	Description	Symbol	Description
C_c	Half wedge Angle	T_t	Tooth thickness
C_t	Half wedge Angle	⊿	Tooth clearance
A_c	Upper corner	H_c	Depth
A_t	Upper corner	H_t	Height
B_c	Lower corner	E_c	Width of tooth profile
B_t	Lower corner	E_t	Width of tooth profile
R_{c1}	Fillet radius	H_{sg}	The height of root stretch
R_{c2}	Fillet radius	D_{sg}	The width of root stretch
R_1	Stretch root fillet	R_{py}	The outer radius of disk
L_c	Shoulder breadth	R_g	Flange radius
L_t	Shoulder breadth	θ	Broaching Angle
S_c	Tooth pitch	D_z	Axial width
S_t	Tooth pitch	N	The number of tenon
T_c	Tooth thickness	Z	The number of mortise

Note: "t" represents tenon, "c" represents mortise.

In order to reduce the number of design variables the DOE method was applied under the iSIGHT platform (iSIGHT is a powerful multidisciplinary optimization software). The calculation process of DOE is shown in Figure 6. Taking mortise subsystem as an example, the Latin hypercube method[16] and orthogonal array method were used to sampling mortise structure geometric parameters in Table 1, and after sampling mortise parametric model and finite element model were updated. Then ANSYS (ANSYS is a finite element analysis software) was used to analyze the mortise structure static strength analysis. Mass and Von Mises Stress were outputed. By comparing the parameter sensitivity analysis results the best influence parameters can be found.

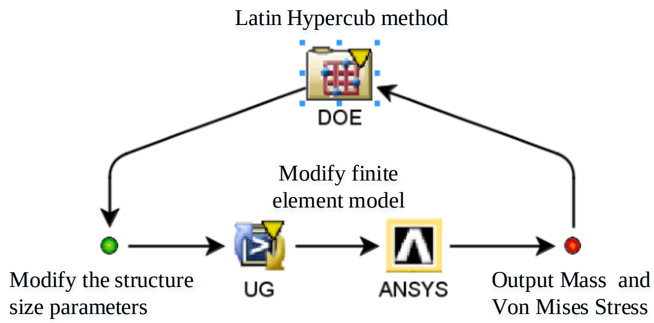


Fig. 6: DOE calculation process

Table 2 shows the optimal design parameters selected by DOE, and the number of design variables reduced from 28 to 16, which greatly improves the computational efficiency.

Tab.2: The optimal design parameters

Symbol	Description	Symbol	Description
C_c	Half wedge Angle	R_1	Stretch root fillet
C_t	Half wedge Angle	L_c	Shoulder breadth
A_c	Upper corner	L_t	Shoulder breadth
A_t	Upper corner	S_c	Tooth pitch
B_c	Lower corner	S_t	Tooth pitch
B_t	Lower corner	H_{sg}	The height of root stretch
R_{c1}	Fillet radius	H_c	Depth
R_{c2}	Fillet radius	H_t	Height

DESIGN OPTIMIZATION FLOW

After completing the DOE, the collaborative optimization method is used to optimize the design of mortise structure. The main system and subsystem optimization objectives are as follows:

- *The target of system-level optimization model is finding minimum mass and minimum Von Mises Stress of the mortise structure.*

$$\min object = 1000m_1 + 300m_2 + 1.05mise_2 + mise_1$$

- *Mortise subsystem optimization goal is to make variance between the mass, Von Mises Stress, S_c', S_t' calculated by subsystem and the corresponding values calculated by the main system minimum.*

$$\min R_1(X_1) = \frac{1}{S_{m1}}(m_1' - m_1)^2 + \frac{1}{S_{mise1}}$$
$$(mise1' - mise1)^2 + \frac{1}{S_{t_c}}(S_c' - S_c)^2 + \frac{1}{S_{t_c}}(S_t' - S_t)^2$$

- *Tenon subsystem optimization goal is to make variance between the mass, Von Mises Stress, S_c', S_t' calculated by subsystem and the corresponding values calculated by the main system minimum.*

$$\min R_2(X_2) = \frac{1}{S_{m2}}(m_2' - m_2)^2 + \frac{1}{S_{mise2}}$$
$$(mise2' - mise1)^2 + \frac{1}{S_{t_c}}(S_c' - S_c)^2 + \frac{1}{S_{t_c}}(S_t' - S_t)^2$$

The optimization models will satisfy their own size and stress constraints and minimize the difference of the subsystem design optimization goal and the main system optimization goal. The main system and subsystem optimization constraints are as follows:

- *The constraints of mortise subsystem (Units: mm and Mpa):*

$$12 \le A_1' \le 22, 30 \le B_1' \le 50, 20 \le C_1' \le 40, 5.4 \le S_c' \le$$
$$25 \le L_1' \le 35, 23 \le H_1' \le 26, 0.8 \le R_{c1}' \le 1.6, 3 \le R_{c2}' \le$$
$$mise1' \le 492$$

- *The constraints of tenon subsystem (Units: mm and Mpa):*

$$12 \le A_2' \le 22, 30 \le B_2' \le 50, 20 \le C_2' \le 40, 5.4 \le S_t' \le 6.8,$$
$$15 \le L_2' \le 21, 20 \le H_1' \le 26, 0.8 \le R_1' \le 1.8, 4.5 \le H_{sg}' \le 8,$$
$$mise2' \le 421$$

- *The constraints of global system (Units: mm):*

$$R_1 = 0, R_2 = 0, h_0 = 0, h_1 = 0, h_2 = 0, 0 \le h_3 \le 1$$
$$h_0 = A_1 - A_2, h_1 = B_1 - B_2, h_2 = C_1 - C_2, h_3 = S_c - S_t$$

The meanings of each parameter in the above formulas are shown in Table 1. Specific optimization mathematical model is shown in Figure 7. The mortise subsystem and tenon subsystem are optimized independently, and the system-level optimizer will satisfy the mortise and tenon assembly constraint compatibility between the two disciplines.

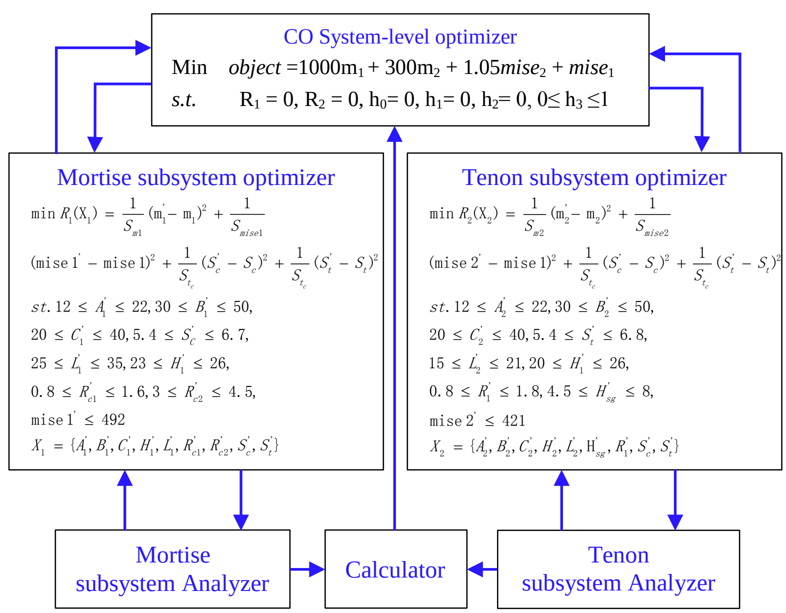


Fig.7: CO optimization model

The last step is using MIGA (Multi-island Genetic Algorithm) to explore the entire design space to get the global optimal solution, and then iteratively update and gradually approach the exact global optimal value through the Non-linear Programming by Quadratic Lagrangian (NLPQL). Finally, the integration work is completed under the iSight platform. The calculation flow is shown in Figure 8.

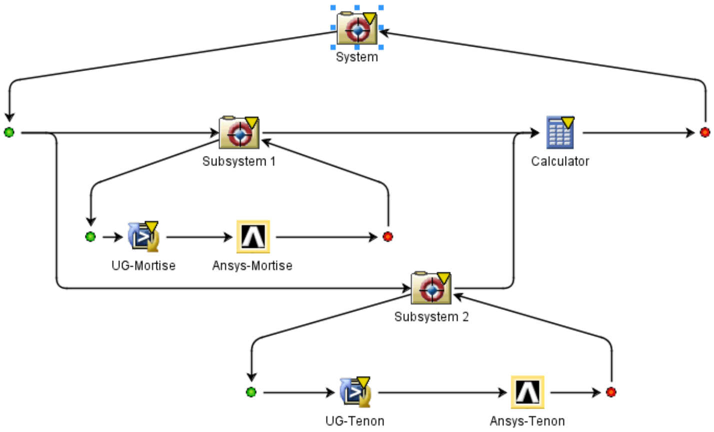


Fig. 8: The calculation flow

RESULTS AND DISCUSSIONS

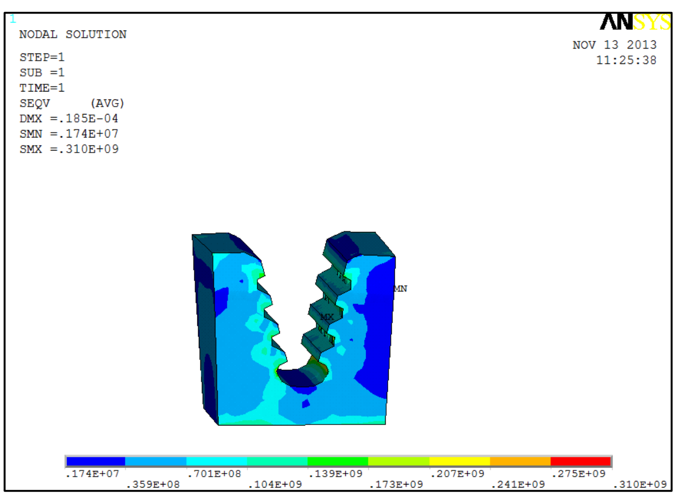
The whole optimization process achieved convergence after 996 iterations. Table 3 shows the values of mass and Von Mises Stress before and after the optimization. Table 4 shows the dimensional change. Figure 9(a-d) shows the Von Mises Stress distribution of mortise and tenon before and after optimization.

Tab.3: Mass (Unit: kg) and Von Mises Stress (Unit: MPa)

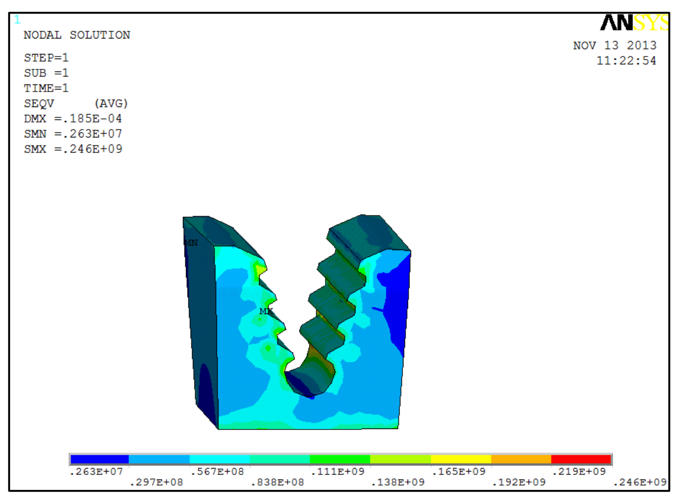
	Mortise			Tenon		
	before	after	reduce	before	after	reduce
Mass	0.5101	0.49238	3.5%	0.17183	0.13754	19.95%
Stress	310	246	20.6%	798	276	65.4%

Tab.4: Dimensional change (Unit:mm)

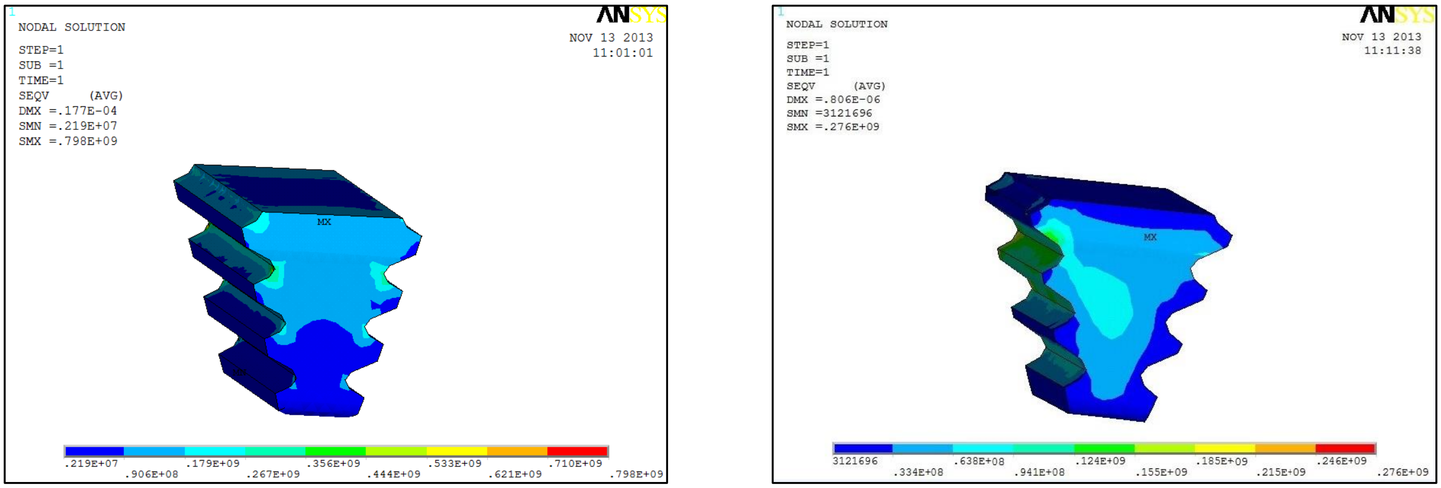
Name	Input	Output	Name	Input	Output
A_c	14	17.034	C_t	30	35.541
B_c	42	47.923	H_t	22	24.983
C_c	30	35.541	L_t	18.2	20.083
H_c	24	25.528	R_c	1.1	1.2986
L_c	25	30.573	H_{sg}	6	5.5
R_{c1}	1.1	1.4695	S_t	6.5	5.8654
R_{c2}	3.75	4.1591	m_c	0.5101	0.49238
S_c	6.5	6.4304	$mise_c$	310	246
A_t	14	17.034	m_t	0.17183	0.13754
B_t	42	47.923	$mise_t$	798	276



(a) The stress distribution of mortise before optimization



(b) The stress distribution of mortise after optimization



(c) The stress distribution of tenon before optimization

(d) The stress distribution of tenon after optimization

Fig. 9: Von Mises stress distribution

After optimization, the mass of the mortise was reduced by 3.5% and the mass of the tenon was reduced by 19.95%, meanwhile the stress of the mortise was reduced by 20.6% and the stress of the tenon was reduced by 65.4%. The results demonstrated the structural performance of mortise and tenon were improved effectively.

CONCLUSIONS

This paper established a multidisciplinary variable coupling optimization method for turbine mortise assembly structure. First through the parameterized technology build a mortise structure model. Second , using the DOE method to obtain the optimal design variables. Third, based on the Collaborative Optimization strategy the mortise structure optimization model is established. Finally, the integration and implementation of the entire method was completed under the ISIGHT platform. The results show that after optimizing the quality and stress of the mortise structure reduced significantly. This method is of strong engineering practicality, it effectively improves the structural performance of the assembly of the mortise-tenon.

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