

# Topology optimization design of the main structure of 6-DOF manipulator based on the variable density method

Yujian RUI<sup>1</sup>, Yongming LIU<sup>1\*</sup>, Zhen ZHANG<sup>1</sup>, Zhijian TU<sup>2</sup>, Jian WU<sup>3</sup>, Neng WEI<sup>2</sup>, Zhuanzhe ZHAO<sup>1\*</sup>

1. School of Mechanical Engineering, Anhui Polytechnic University, Anhui Wuhu 241000, China

2. Wuhu Ceprei Robotics Industry Technology Institute Co., Ltd., Anhui Wuhu 241000, China

3. Wuhu Institute of Technology, Anhui Wuhu 241000, China

**\*Corresponding Author:** Yongming LIU, Wuhu, 241000, China, liuyongming1015@163.com; Zhuanzhe Zhao, Wuhu, 241000, China, zhuanzhe727@ahpu.edu.cn

## Abstract:

In order to solve the problems of too large mass, too complex structure and poor flexibility of the 6-DOF manipulator, the topological optimization theory based on variable density method is applied to the 6-DOF manipulator, the topology optimization of the main structural components of the manipulator is carried out with the help of the finite element software ANSYS, and the optimized structure is simplified according to the density distribution of the units and the requirements of manufacturability, the results are compared and analysed by static mechanics. It shows that the whole mass of the 6-DOF manipulator is reduced by 47.23% without changing the original mechanical properties after topological optimization, and the optimized model can meet the requirements of manufacturability, the optimization effect is significant, which can be used as a reference for the structure optimization of the 6-DOF manipulator.

**Keywords:** Variable density method; topology optimization; 6-DOF manipulator; finite element analysis

## Introduction

Six-degree-of-freedom manipulators are widely used in the field of industrial robots. As the executing mechanism of the robot, the tiny deformation of the components of the robot arm is related to its control accuracy, and the stress state of the material will affect the service life of the robot arm, the change of these factors will make the overall use of the robot effect changes. The structural optimization of 6-DOF arms mostly depends on the manufacturing experience of engineers, and the theory of topology optimization is seldom used.

Topology optimization is to get the best distribution scheme and the best load-transfer path in a given design space, taking the material distribution as the optimal objective function. The concept of topology optimization, which originated from the problem of structural design, has now been widely applied in many fields, such as heat <sup>[1]</sup>, fluid mechanics <sup>[2]</sup>, acoustics <sup>[3]</sup>, electromagnetism <sup>[4]</sup>, optics <sup>[5]</sup> and the combination of multiple disciplines. At present, the common methods of Continuum topology optimization are variable density method <sup>[6]</sup>, evolutionary

structural optimization method <sup>[7]</sup>, level set method <sup>[8]</sup> and so on.

In order to solve the problems of the 6-DOF manipulator which is too heavy and the fuselage structure is too complex, the variable density topology optimization method is used to carry on the topology optimization analysis in ANSYS software, the structure of the manipulator is optimized reasonably, and then the optimized model is re-introduced into the ANSYS software according to the optimized cloud chart, and the stress, stress and deformation are analyzed and compared, thus realizes to the main body structure supplement optimization.

## 1 Topology optimization theory based on variable density method

The variable density method is a topological optimization method based on the description of the physical properties of isotropic materials, at the same time, it is assumed that the pseudo-density is also the relation between the material density and the material characteristics of each unit and the elastic coefficient. At present, the common interpolation models are penalty

interpolation model or rational approximation model of material properties<sup>[9]</sup>. In order to make the intermediate density approach to interval, a penalty factor is introduced to punish the intermediate density, the SIMP method based on variable density theory is adopted. The variable density method has the advantages of high calculation efficiency and easy solution. The mathematical expression is as follows:

$$\rho = X_e \rho_0 \quad (1)$$

Where  $X_e$  is the relative density of the elements;  $\rho_0$  is the inherent density of each element; and  $\rho$  is the topology optimization design variable. When  $X_e = 1$ , all structural materials are retained; when  $X_e = 0$ , all structural materials are eliminated. Because of the discontinuity of  $\rho$ , the design variables must be continuous in topology optimization, and the upper formula must be solved by derivation.

$$K_e = (X_e)^p K_0 \quad (2)$$

Where  $K_e$  is the stiffness of the element,  $K_0$  is the inherent stiffness of the element and  $p$  is the penalty factor. Equation (2) can be written as

$$C(x) = F^T U = U^T F U \quad (3)$$

Where  $C(x)$  is the structural compliance;  $F$  is the Load Vector;  $K$  is the Global Stiffness Matrix;  $U$  is the displacement vector. For constrained volume, in order to maximize material stiffness, the topology optimization based on variable density method can be written as

$$\begin{aligned} \text{Find: } & x = \{x_1, x_2, x_3, \dots, x_n\} \\ \text{Minimize: } & C(x) = F^T U \\ \text{Subject to: } & \begin{cases} f = \frac{V - V_1}{V_0} \\ 0 \leq x_{\min} \leq x_e \leq x_{\max} \\ F = KU \end{cases} \end{aligned} \quad (4)$$

Where  $n$  is the total number of elements;  $x_e$  is the design variable, which represents the relative density of the  $e$  element;  $v$  is the volume of the structure before optimization;  $V_0$  is the volume of the structure design area;  $V_1$  is the volume with density less than 1;  $f = \frac{V - V_1}{V_0}$  is the volume constraint equation;  $x_{\min}$  is the lower limit of element density and  $x_{\max}$  is the upper limit of element density. In order to avoid singularity of stiffness matrix,  $x_{\min} = 0.001$ .  $F = KU$  is a finite element equilibrium equation constraint.

In the variable density topology optimization method, the design variable can take any density value in. When the relation between elastic modulus and relative density is constant, different interpolation modes produce different models. The formula of SIMP method for interpolation model is

$$E(x_i) = E_{\min} + x_i^p (E_0 - E_{\min}) \quad i = 1, \Lambda, n \quad (5)$$

Where  $E$  is the interpolated modulus of elasticity,  $E_0$  is the initial modulus of elasticity,  $p$  is the penalty factor, and  $E_{\min}$  is the modulus of elasticity of the blank cell, in general,  $E_{\min}$  usually takes a minimum value to ensure that the stiffness moment singularity does not occur during the optimization process.

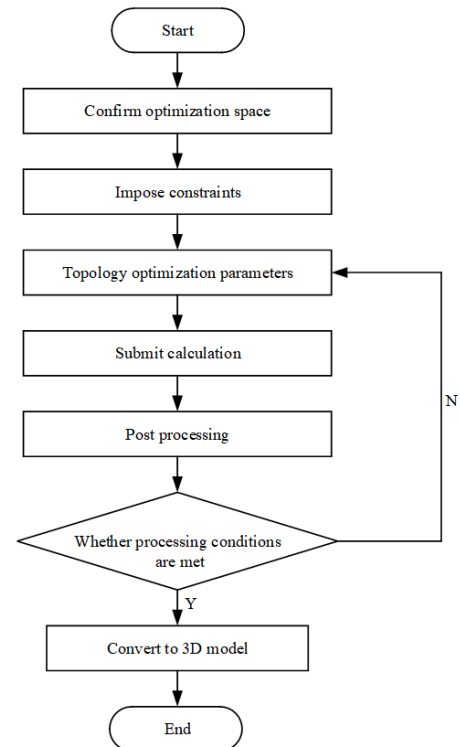
In the process of topology optimization of continuum structures by variable density method, numerical instability often occurs, because the grid division is needed in the pre-processing, in order to avoid the influence of numerical instability on the final optimization results, the sensitivity filtering technique is used in the optimization process. The sensitivity filtration technique is to filter and correct the sensitivity of each unit in the material. The formulas are as follows

$$\frac{\partial c}{\partial x_i} = \frac{1}{x_i \sum_{j=1}^{N_i} H_{ij}} \sum_{j=1}^{N_i} H_{ij} x_i \frac{\partial c}{\partial x_i} \quad (6)$$

$$H_{ij} = \max(0, r_{\min} - \Delta(i, j)) \quad (7)$$

Where  $x_i$  is the sensitivity;  $r_{\min}$  is the filter radius;  $N_i$  is the number of elements in the filter radius  $r_{\min}$  with  $i$  as the center;  $H_{ij}$  is the weight equation;  $\Delta$  is the central distance between unit  $i$  and Unit  $j$ .

The technical route of variable density topology optimization of the main body of the manipulator is shown in Figure 1.



**Figure 1** Technical route of topology optimization with variable density method

The topology optimization process is as follows:

(1) Define the design area, determine the material parameters, design the area grid division, determine the

different grid division parameters for the different main structure, determine the space to be optimized;

(2) Establish the correct boundary conditions, determine the load conditions, constraints are imposed;

(3) The parameters of topology optimization are set according to the actual demand;

(4) The parameters are calculated and analyzed;

(5) The updated design variables are compared with the optimization parameters to judge whether they meet the requirements;

(6) Repeat steps 3-5) until the processing conditions are met;

(7) Remodel the optimized structure.

## 2 Topology optimization design of main parts

The structural optimization design of the 6-DOF manipulator mainly lies in the three parts of the small arm, the big arm and the rotating base, the objective function is set as the compliance of the model, and the mass of the material is defined as a variable in the response constraint of Ansys, and the maximum stress, strain and volume are taken as the constraints.

Ansys Workbench 19.0 software already has a complete topology optimization module, which integrates the objective function and constraints without the need to use the APDL language by itself. For the optimization principle of constant stiffness and volume reduction of the model before and after topology optimization, the same constraints are applied to the model before and after the optimization and the static analysis is performed respectively. The validity of the optimization results can be obtained by comparing the total deformation data before and after optimization. The total deformation data before and after optimization should not change too much.

**Table 1** Material properties.

Material	Density [Kg mm <sup>-3</sup> ]	Elasticity modulus [Pa]	Poisson ratio	Tensile strength [Pa]	Yield strength [Pa]
45#	7850	2.1e+11	0.269	6e+8	3.55e+8

### 2.1 Topology optimization of the small arm

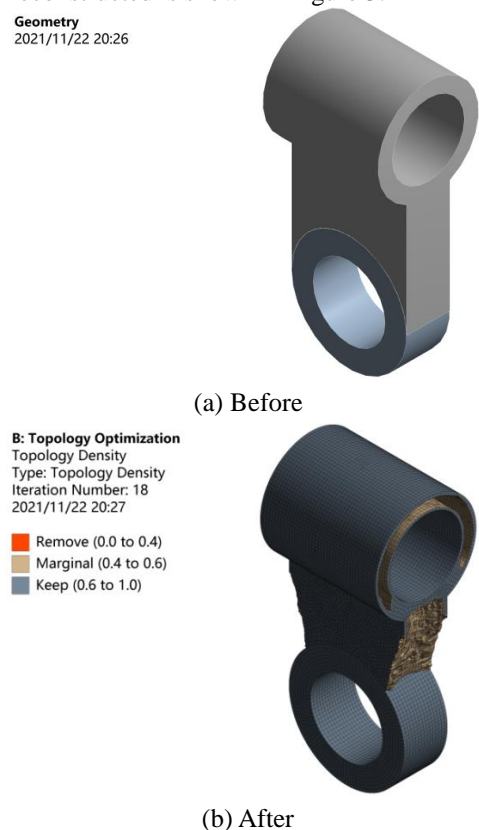
The main control arm of the manipulator vertical up and down two aspects of the displacement, the arm topology optimization design, the quality constraints of 50% , for the optimization of the small arm structure before and after the design as shown in Figure 2.

After topological optimization of the small arm, the density of the part originally connected with the bearing hole is effectively reduced. The overall volume is reduced from 3.499e+5 mm<sup>3</sup> to 1.9411e+5 mm<sup>3</sup>, and the optimized volume is 55.477% of the original volume; The mass is reduced from 2.7467 Kg to 1.5238 Kg, and the optimized mass is 55.477% of the original mass.

As can be seen from the density distribution diagram, the bearing holes of the boom are optimized and reduced,

and the overall optimized model is rough and irregular, so that the model can be manufactured later, the simplified model is processed according to the density distribution of the model and the requirement of manufacturing, which makes the simplified model have the same performance as the original structure. The topology optimization module of Ansys, "Spelclaim", is used to obtain a complete 3D model of the optimized model and to modify the optimized model. According to the principle of not changing the density distribution of the model itself after optimization and easy manufacturing and processing, the rough and convex parts of the original optimized model surface are smoothed. The simplified model reconstructed is shown in Figure 3.

Geometry  
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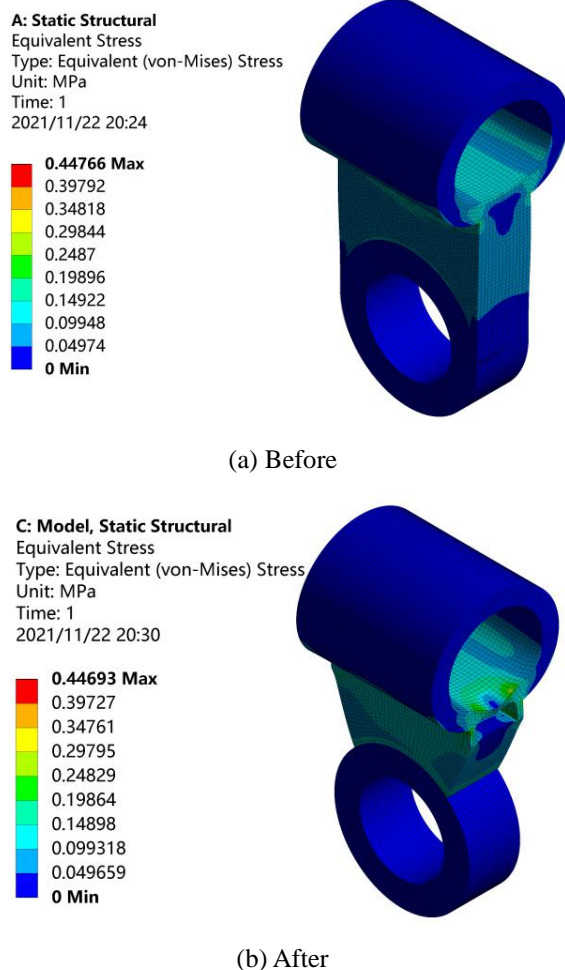


**Figure 2** Comparison of fore-and-aft optimization of small arm model.



**Figure 3** Simplified model of small arm after optimization

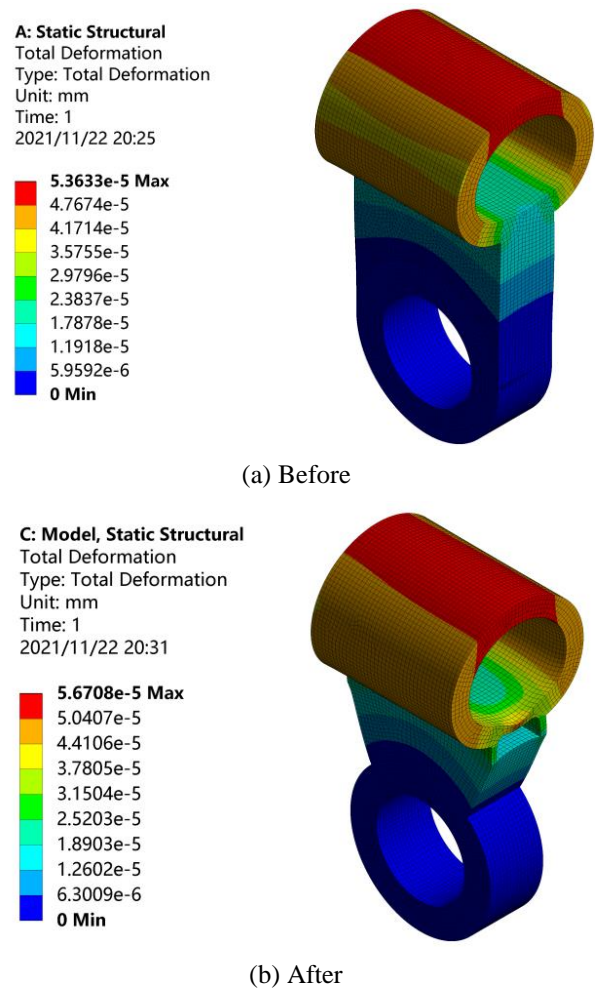
The static analysis of the simplified model before and after optimization is carried out under the same conditions. A load of 200 N is applied in the bearing bore, and the type of load action is "BearingLoad", which can better reflect the force distribution in the bearing bore. "BearingLoad" usually adopts the method that the load is distributed on the contact surface of the shaft and the hole according to the sinusoidal law, assuming that the magnitude of the acting force is distributed according to the sinusoid. This method is widely used in practice because of the simple law and good compliance for the simple structure of holes and shafts ( The following forces are the same type of load action). The results of the static analysis are shown in Figure 4.



**Figure 4** Equivalent stress Nephogram of small arm before and after optimization

It can be seen from Figure.4 that the maximum stress before and after the optimization of the boom appears at the position of the connecting part of the bearing hole and the connecting plate, where the fillet is not added, resulting in the stress concentration after loading, but the total stress is still within the yield strength of the material, and the maximum stress before optimization is 0.44766 MPa, and the maximum stress after optimization is 0.44693 MPa, its static strength is still within the yield

strength of the material.



**Figure 5** Displacement Diagram of total deformation of small arm before and after optimization

From Figure.5, it can be seen that the maximum deformation displacement is 5.3635e-5mm before optimization and 5.6708e-5mm after optimization, there is little difference in displacement and deformation before and after optimization. According to the simulation data, the arm has the same resistance to deformation before and after optimization, and the optimized quality is 55.477% of the original quality, and the optimized quality is greatly reduced. The specific data changes before and after optimization are shown in Table 2.

**Table 2** Changes of mechanical properties of small arm before and after optimization.

Optimization process	Mass (Kg)	Maximum total deformation (mm)	Maximum stress (MPa)
Before	2.7467	5.3635e-5	0.44766
After	1.5238	5.6708e-5	0.44693

## 2.2 Topology optimization of big arms

The big arm mainly controls the change of the



horizontal displacement of the manipulator before and after, when the topology of the big arm is optimized. The optimization model uses the most original structure quality is big, the optimization space is very big, therefore sets the quality to retain the original quality 30% , regarding optimizes before and after big arm's structure design as shown in Figure 6.

As can be seen from Figure.6, the optimized position is the connecting rod of two bearing holes and a part of bearing holes. The optimized density unit is reasonable. The overall volume is reduced from  $7.6992e+5 \text{ mm}^3$  to  $3.8166e+5 \text{ mm}^3$ . The optimized volume is 49.57% of the original volume, the original mass was optimized from 6.0439 Kg to 2.996 Kg, and the optimized volume was 49.57% of the original volume.

**B: Topology Optimization**  
Solution  
Iteration Number: N/A  
2021/11/22 20:33



(a) Before

**B: Topology Optimization**  
Topology Density  
Type: Topology Density  
Iteration Number: 21  
2021/11/22 20:35

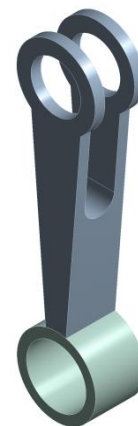
Remove (0.0 to 0.4)  
Marginal (0.4 to 0.6)  
Keep (0.6 to 1.0)



(b) After

**Figure 6** Model comparison before and after big arm optimization

Similarly, the optimized arm model is simplified to meet the requirements of post-processing and the original density distribution. The simplified arm model is shown in Figure.7.



**Figure 7** Simplified model of big arm after optimization

The static analysis of the simplified model before and after optimization is carried out under the same conditions. The applied bearing load is 200 N. The results of the static analysis are as follows.

**A: Static Structural**  
Equivalent Stress  
Type: Equivalent (von-Mises) Stress  
Unit: MPa  
Time: 1  
2021/11/22 20:34

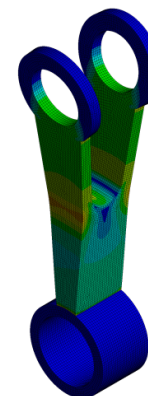
0.6442 Max  
0.57262  
0.50105  
0.42947  
0.35789  
0.28631  
0.21473  
0.14316  
0.071578  
5.7908e-13 Min



(a) Before

**C: Model, Static Structural**  
Equivalent Stress  
Type: Equivalent (von-Mises) Stress  
Unit: MPa  
Time: 1  
2021/11/22 20:37

0.43034 Max  
0.38253  
0.33471  
0.2869  
0.23908  
0.19126  
0.14345  
0.095632  
0.047816  
0 Min

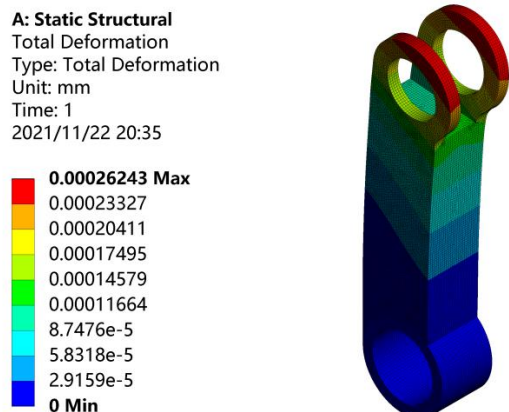


(b) After

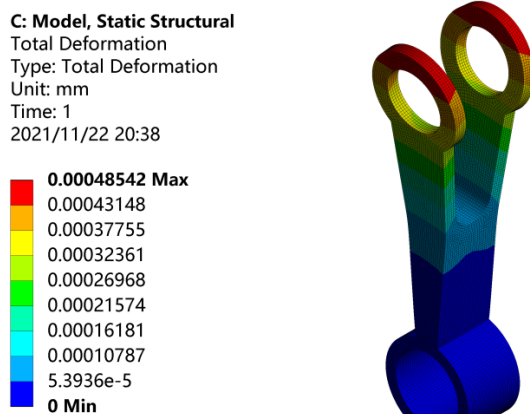
**Figure 8** Equivalent stress Nephogram of big arm before and after optimization

As can be seen from Figure.8, the stress concentration area of the arm is between the bearing hole and the connecting Rod. The maximum stress before optimization is 0.6442 MPa, and the maximum stress after optimization is 0.43034 MPa. The stress of the optimized model is less

than that before optimization, the static strength of the optimized model is better than that of the pre-optimized model, and it is all within the yield strength of the material.



(a) Before



(b) After

**Figure 9** Total deformation displacement diagram before and after big arm optimization

As can be seen from Figure.9, the maximum deformation displacement is 0.00026243 mm before optimization and 0.00048542 mm after optimization. The amount of deformation after optimization is slightly higher than the amount before optimization, but here according to our actual needs is to design this part as light as possible, so the quality of the parts to be greatly optimized, although the deformation resistance decreases slightly, the maximum deformation is still within the acceptable range, the stress decreases and the density distribution of the structure is reasonable, so the topological optimization results are also acceptable, the structure design achieves the expected ideal.

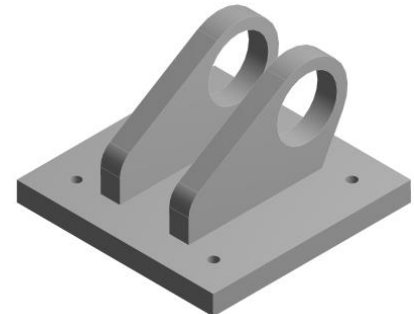
**Table 3** Comparison of mechanical properties of big arms before and after optimization.

Optimization process	Mass (Kg)	Maximum total deformation (mm)	Maximum stress (MPa)
Before	6.0439	0.00026243	0.6442
After	2.996	0.00048542	0.43034

## 2.3 Topology optimization of rotating base

The rotating base part mainly controls the movement of the XY axis of the manipulator, and sets the quality restriction to 50% of the original mass according to the actual demand. Before and after the model is optimized for the rotating base, as shown in Fig.10.

Geometry  
2021/11/22 20:42



(a) Before

**B: Topology Optimization**  
Topology Density  
Type: Topology Density  
Iteration Number: 13  
2021/11/22 20:46

Remove (0.0 to 0.4)  
Marginal (0.4 to 0.6)  
Keep (0.6 to 1.0)

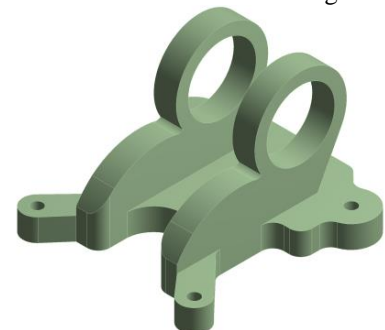


(b) After

**Figure 10** Model comparison before and after optimization of rotating base

As can be seen from Figure. 10, the optimized density unit is mainly located at the base support plate. The overall volume of the structure decreased from 1.1439e+6mm<sup>3</sup> to 6.1887e+5mm<sup>3</sup>, the overall volume decreased to 54.1% of the original volume, the overall mass decreased from 8.9798Kg to 4.8582Kg, and the overall mass decreased to 54.1% of the original volume, the simplified model reconstructed is shown in Figure11.

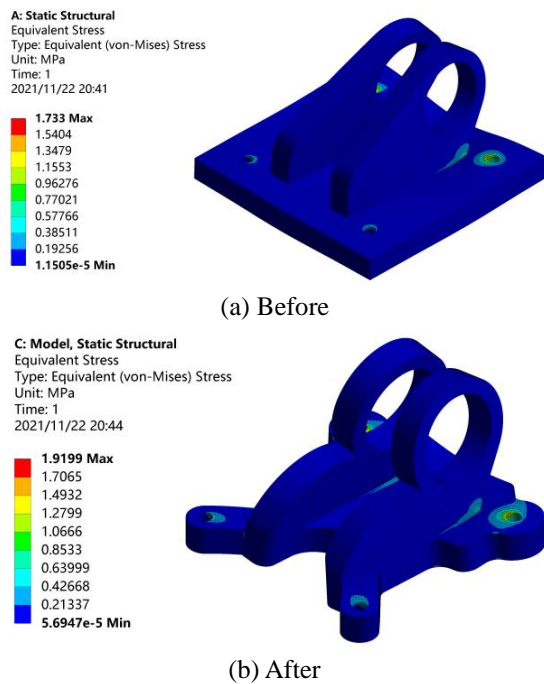
Geometry  
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**Figure 11** Simplified model after optimization of rotating base

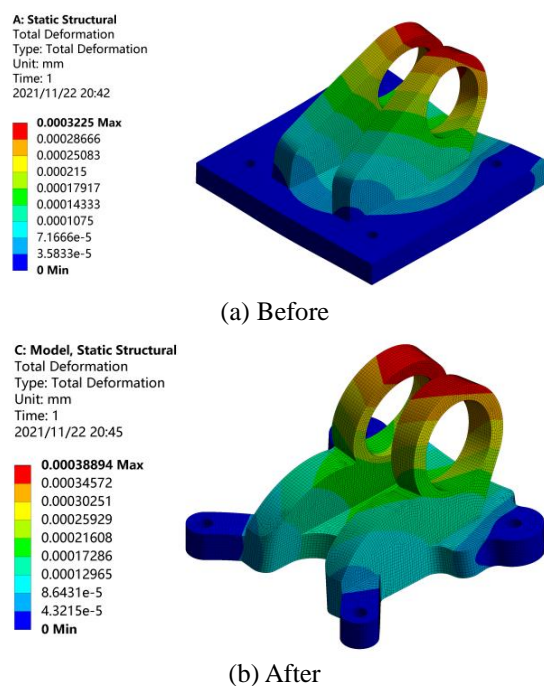
Static analysis was carried out on the preoptimized and post-optimized simplified models under the same

conditions. The applied bearing load was 200N. The results of static analysis are shown in Figure12.



**Figure 12** Equivalent stress nephogram before and after optimization of rotating base

As can be seen from Figure12, the maximum stress is at the bolt hole, where the stress is concentrated. The maximum static stress of the structure is 1.733 MPa before optimization and 1.9199 MPa after optimization, and the stress rises slightly after optimization, but the change range is only 10.7% , which is still within the compressive strength of the material.



**Figure 13** Displacement Diagram of total deformation before and after optimization of rotating base

As can be seen from Figure13, the maximum deformation is 0.0003225mm before the whole structure is optimized and 0.00038894mm after the whole structure is optimized, it can be regarded as the same anti-deformation ability before and after optimization, and its structure design achieves the expected ideal.

A summary of the data before and after the rotation base optimization is shown in Table 4.

**Table 4** Comparison of mechanical properties of rotating base before and after optimization.

Optimization process	Mass (Kg)	Maximum total deformation (mm)	Maximum stress (MPa)
Before	8.9798	0.0003225	1.733
After	4.8582	0.00038894	1.9199

### 3 Conclusion

The results of static analysis before and after optimization show that the mass of the manipulator is 17.7704 Kg before optimization and 9.378 Kg after optimization, and the total mass is reduced by 47.23%, the optimized model structure is more concise, the whole structure is more flexible when working, and the optimal effect is remarkable. Without changing the original mechanical properties, only the material distribution in the design area is changed, which shows that it is effective to apply the topology optimization method of variable density method to the 6-DOF manipulator, and the effect is remarkable. Through the application of this theory, the mass of the structure is reduced effectively and the lightweight design of the manipulator is achieved. At the same time, the optimized model is simplified by post-processing, which also makes the optimized model meet the requirements of manufacturability and machinability, and plays a reference role for the follow-up structure optimization of 6-DOF manipulator.

### Conflict of Interest

The authors declares that there is no conflict of interest regarding the publication of this paper.

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