Structural Parameter Optimization of Robotic Arm Based on ABAQUS

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Abstract. The structural parameters of robotic arms are crucial for industrial production safety and cost efficiency. However, the complex relationships between structural parameters (e.g., cross-sectional shape, area ratio, and rear-end area) and mechanical performance are challenging to express using simple mathematical formulas. To scientifically predict the load-bearing capacity of robotic arms with specific structural parameters, this study employs ABAQUS software to conduct static load simulations on robotic arms with varying parameters. The simulation data are optimized using the NSGA-2 algorithm to generate a Pareto solution set for maximum stress and displacement. Subsequently, the entropy weight method is applied to calculate the weights of these two indicators, and the TOPSIS algorithm is utilized to screen the optimal solution. The results demonstrate that under a given load, the robotic arm with a circular cross-section, an area ratio of 0.96, and a rear-end area of 39.80 mm² exhibits the highest load-bearing capacity. Compared with traditional robotic arm optimization methods, this paper combines the comprehensive evaluation method with the multi-objective optimization method to achieve the goal of selecting the best among the best data of the robot arm in the optimization solution set. This method can not only meet the requirements of the robot arm for the structure and mechanical properties, but also make the optimization results more excellent, which has important guiding significance for improving the manufacturing process design of the robot arm.

Keywords: ABAQUS Simulation, NSGA-2 Algorithm, TOPSIS Algorithm, Structural Parameter Optimization.

1. Introduction

Robotic arms, composed of linkages and attachments, are critical components in industrial automation, robotics, and agricultural machinery. Optimizing their structural parameters is essential for enhancing performance and reducing costs. Current research primarily focuses on motion-related parameter optimization and lightweight design under static conditions. For one thing, Wang Rui employed the Monte Carlo method and adaptive meshing technique to analyze the influence of linkage length and rotation angle on workspace [1]. When Liu Jiang optimized the heavy-duty robot arm, he gave the influence of the rounded Angle size, step position and structure on the stress of the robot arm [2]. Yue Jianrong et al. derived the optimal link lengths and rotation angles for a 5-degree-of-freedom agricultural robotic arm using MATLAB [3]. Sun Kai combined the response surface method with Monte Carlo simulations to optimize the thickness of a robotic arm's main plate under mechanical reliability constraints [4]. Jiang Mingming et al. used SolidWorks to simulate key components of a pipeline robot equipped with a rust removal robot arm, and optimized the structure of the robot arm with quality and deformation as constraints [5]. Zhang Qing et al. proposed a vibration-damping design for composite flexible robotic arms through Simulink modeling and experimental validation [6]. Du Xiaofeng et al. used Solidworks and Ansys to model and analyze the structure of the mechanical arm with specific parameters and verify its bearing performance, but did not compare the impact of the mechanical arm with different parameters on the bearing performance [7].

For another, Wang Yuchao et al. used the response surface method and multi-objective genetic algorithm to analyze the weight loss of the robotic arm, and optimized the parameters of the arm length and width [8]. Jiang Hao et al used the AHPS-entropy weight TOPSIS method to evaluate the interaction quality of the teaching platform of the robot arm [9], Xu Yangyang et al used the advanced optimization algorithm to optimize the structure of the robot arm [10], and Wu Fei et al used the NSGA-II algorithm to optimize the motion trajectory of the robot arm [11]. Wei Wenqing et al. used RSM algorithm and NSGA-II algorithm to optimize the structural design of robotic arm [12]. While existing studies extensively address motion characteristics and lightweight design, and evaluation algorithms such as topsis and optimization algorithms such as NSGA-II are widely used. The impact of cross-sectional shape and area variations on load-bearing capacity remains underexplored. This study integrates ABAQUS simulations, NSGA-2 multi-objective optimization, and entropy-weighted TOPSIS decision-making to systematically investigate these factors, providing a practical framework for enhancing robotic arm manufacturing processes.

2. 3D Geometric Modeling and Static Simulation

2.1. 3D Geometric Modeling

The geometric models were constructed in SOLIDWORKS based on predefined parameters (Table 1 and Table 2). For example, Group 1 represents a circular cross-section with an A-end area of 40 mm² and a B-end area of 32 mm². The geometric model built by SolidWorks in this paper is shown in Figure 1. Since the cross-sectional shape is hexagonal (Shape=0), with both A-end and B-end areas set to 20 mm² (Area=-1) and an area ratio of 1.0 (Area Ratio=1), this geometric model corresponds to Group 6 based on the parameter definitions in Table 2.

Table 1. Simulation Group Parameters

Group	1	2	3	4	5	6	7	8	9	10	11	12	13
Shape	-1	0	1	-1	1	0	0	-1	0	0	-1	1	1
Area	1	1	1	-1	0	-1	0	0	1	-1	0	0	-1
Area Ratio	0	1	0	0	1	1	0	-1	-1	-1	1	-1	0

Table 2. Parameter Level Definitions

Level	Shape	Area (mm2)	Area Ratio
-1	Circular	20	0.6
0	Hexagonal	30	0.8
1	Triangular	40	1

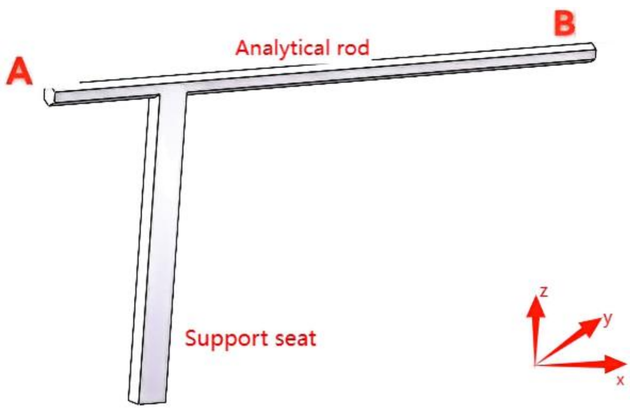

Figure 1. Geometric Model Schematic

2.2. Static Simulation Results

ABAQUS simulations were performed using steel material properties (Young's modulus: 210 GPa, Poisson's ratio: 0.3). Fixed constraints were applied to the base, while distributed gravity (9.81 m/s²) and a 100 N point load at the B-end were imposed. Maximum stress and displacement for each model are summarized in Table 3.

Table 3. Simulation Results

Group	1	2	3	4	5	6	7	8	9	10	11	12	13
Max Stress (MPa)	545.50	470.00	420.90	1586.00	643.10	2023.00	1700.00	855.20	1151.00	2207.00	577.10	4080.00	2906.00
Max Displacement (mm)	2.03	1.49	1.39	4.10	2.21	19.14	11.21	3.18	8.51	27.57	3.18	11.39	18.68

3. Multi-Objective Optimization and Decision-Making

In this paper, it is necessary to optimize the maximum stress and maximum displacement (function expression), which can not reach the minimum at the same time. Therefore, this paper first uses nsga-2 algorithm to optimize the maximum stress and displacement to obtain the Pareto solution set, and then uses entropy weight method to calculate the weight of the two indicators of maximum stress and displacement, and finally uses TOPSIS algorithm to screen the optimal results.

3.1. Double objective optimization based on NSGA-2 algorithm

In this paper, nsga-2 algorithm is used to optimize the maximum stress and displacement index of the manipulator. The specific steps are shown in the following Figure 2.

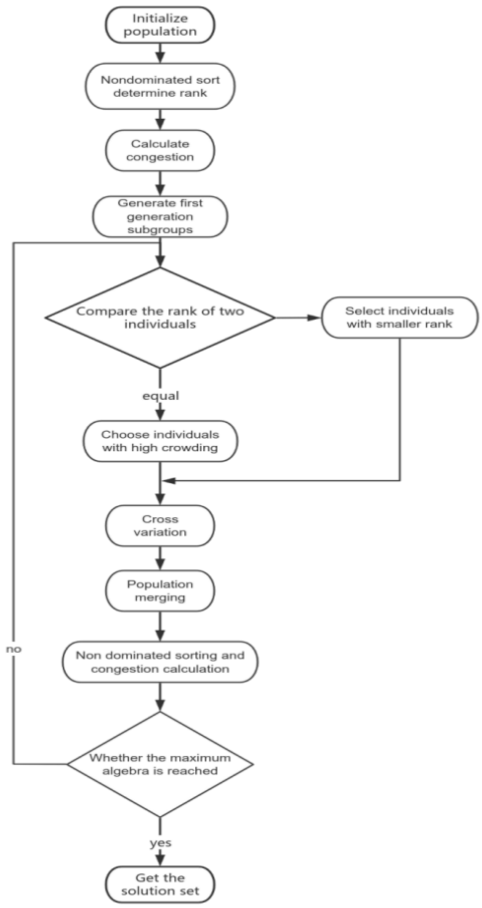

Figure 2. Double objective optimization flow chart based on nsga-2 algorithm

3.1.1 Optimization results of NSGA-2 algorithm

Set the NSGA-2 cross ratio as 0.61, mutation probability as 0.005, initial population number as 50, iterative algebra as 400, and use matlab toolbox to find the Pareto solution set. Some data are shown in Table 4.

Table 4. Pareto Solution Set

[Shape, Area, Ratio]	Displcement	Max Stress
[0, 38.3316600000000, 0.894815800000000]	0.008978665	694.9602215
[0, 38.6968840000000, 0.824438700000000]	0.008978665	694.9602215
[0, 35.4798440000000, 0.988315700000000]	0.012630793	487.8471525
[-1, 39.7951680000000, 0.988315700000000]	3.283888619	441.3429389
[-1, 39.7951680000000, 0.977158300000000]	3.283888619	441.3429389
[-1, 39.7951680000000, 0.957296400000000]	9.981772286	388.3470327
[-1, 39.7951680000000, 0.988315700000000]	9.981772286	388.3470327
[-1, 39.7951680000000, 0.894815800000000]	10.33778875	383.0258413
[-1, 39.7951680000000, 0.676634400000000]	10.97155318	373.5532966
[-1, 39.7951680000000, 0.696395400000000]	10.97155318	373.5532966

3.2. Entropy-Weighted TOPSIS Decision

In this paper, the entropy weight method is used to calculate the weight of the maximum stress and displacement, and then TOPSIS is used to evaluate and rank them to get the optimal result.

(1) Normalization of Pareto disaggregation index data.

$$X_{\min} = \min\left(X_{1j}, X_{2j}, \dots, X_{nj}\right) - 0.0001 \tag{1}$$

$$X_{\max} = \max\left(X_{1j}, X_{2j}, \dots, X_{nj}\right) + 0.0001 \tag{2}$$

$$z_{ij} = \frac{X_{\max} - X_{ij}}{X_{\max} - X_{\min}} \tag{3}$$

(2) Calculation of index entropy.

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln\left(p_{ij}\right),\ j = 1, \cdots, m \tag{4}$$

$$k = 1/\ln(n) > 0,\ e_j \geq 0 \tag{5}$$

(3) Calculation of index information entropy redundancy.

$$d_j = 1 - e_j,\ j = 1, \cdots, m \tag{6}$$

(4) Calculation of index weight.

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j},\ j = 1, \cdots, m \tag{7}$$

(5) Define positive ideal distanceZ^+Distance from negative idealZ^-.

$$Z^+ = (Z_1^+, Z_2^+, \cdots, Z_m^+) = (\max\{z_{11}, z_{21}, \cdots, z_{n1}\}, \cdots, \max\{z_{1m}, z_{2m}, \cdots, z_{nm}\}) \tag{8}$$

$$Z^- = (Z_1^-, Z_2^-, \cdots, Z_m^-) = (\min\{z_{11}, z_{21}, \cdots, z_{n1}\}, \cdots, \min\{z_{1m}, z_{2m}, \cdots, z_{nm}\}) \tag{9}$$

(6) Calculation of the difference between the normalized result of the index and the positive and negative ideal distance.

$$D_{\mathrm{j}}^+ = \sqrt{\sum_{j=1}^{m} w_j \left(Z_j^+ - z_{ij}\right)^2} \tag{10}$$

$$D_{\mathrm{j}}^- = \sqrt{\sum_{j=1}^{m} w_j \left(Z_j^- - z_{ij}\right)^2} \tag{11}$$

(7) Calculate the score of the index and select the optimal solution.

$$G_i = \frac{D_j^-}{D_j^+ + D_j^-} \tag{12}$$

3.3. Optimal solution decision result

(1) In this paper, the weight of maximum stress and displacement is calculated by entropy weight method, and their respective weights in the design of mechanical arm are obtained. The results are shown in Table 5.

Table 5. Indicator Weights

Indicator	Weight
Max stress	85.934%
Displacement	14.066%

(2) In this paper, through AHP-Topsis algorithm, the Pareto solution set in Table 4 is evaluated, and the evaluation results are shown in Table 6.

Table 6. Top 10 Solutions

Shape	Area	Ratio	Displacement	Max Stress	Rank
-1	39.80	0.96	9.98	388.35	1
-1	39.80	0.68	10.97	373.55	2
-1	39.80	0.77	12.97	343.76	3
0	38.33	0.89	0.01	694.96	4
-1	39.80	0.99	3.28	441.34	5
-1	39.80	0.99	9.98	388.35	6
-1	39.80	0.80	19.93	239.70	7
1	39.80	0.94	16.97	283.91	8
1	38.25	0.96	15.92	299.58	9
1	39.80	0.94	17.42	277.16	10

It can be seen from the above table that the overall structure of the manipulator is the best when the section shape of the manipulator is circular, the section area ratio is 0.96, and the a interface area is 39.80.

4. Conclusion

Based on ABAQUS simulation and multi-objective optimization algorithm, this study systematically explores the influence of the structural parameters of the manipulator (section shape, section area ratio, rear end section area) on its bearing performance, and puts forward the optimization design method. The main conclusions are as follows:

(1) The effect of parameter optimization is remarkable: the maximum stress and displacement are multi-objective optimized by nsga-2 algorithm, and the Pareto solution set is obtained. Combined with entropy weight method, the index weight (maximum stress weight 85.934%, displacement weight 14.066%) is determined, and the optimal solution is selected by TOPSIS algorithm. The results show that when the section shape of the manipulator is circular, the section area ratio is 0.96, and the rear section area is 39.80 mm^2, it has the maximum bearing capacity under the given load, which verifies the effectiveness of the proposed method.

(2) The key role of section shape: the simulation and optimization results show that the circular section is better than the hexagonal and triangular section in reducing stress concentration and improving structural stability, which provides an important reference for the lightweight and high load-bearing design of the manipulator.

(3) Method innovation: by integrating finite element simulation, multi-objective optimization and decision-making algorithm, this study solves the problem that it is difficult to quantify the relationship

between complex parameters and mechanical properties in traditional research, and provides a systematic solution for the structural optimization of manipulator.

(4) Practical application value: the optimized parameter combination can be directly applied to the manufacturing process design of the manipulator, improve the bearing efficiency on the premise of ensuring safety, and has guiding significance for the structural optimization of industrial robots, agricultural machinery and other fields.

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