Structure Optimization of Mechanical Boom Based on Whale Algorithm

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Abstract. The finite element simulation and analysis of the deformation process of the mechanical boom carrying heavy loads is carried out in Ansys software, and the outer radius of the cross-section circle, cross-section shape, distance of the support point and the ratio of cross-sectional area at both ends of the boom are taken as the structural parameter variables, and the four-factor, four-level orthogonal test L_{16} is designed. The total deformation and the equivalent force during the deformation process of the boom loaded with weight are taken as the indicators of the evaluation of the load carrying capacity, meanwhile the regression analysis software SPSS was used to find the regression equation. This research is innovative on the basis of previous experiments. In this process of research, the application of multi-domain simulation software skills including modeling, structural mechanics analysis, data analysis, and algorithms is taken. In this paper, the Whale Optimization Algorithm (WOA) was introduced to optimize the results of orthogonal tests to obtain the optimal combination of process parameters. The results show that, from the data set in this research, when the radius of the external circle is 38.9mm, the cross-section shape is circular, the distance between support points is 66.12mm, and the ratio of the cross-sectional area of the two ends of mechanical boom is 0.94, the deformation and the equivalent force of the mechanical boom when subjected to the vertical downward force of 1000N are minimized, and the structure is optimal. The deformation is 0.035mm and the equivalent force is 353500000pa. The simulation results have good reliability and can provide theoretical guidance for actual production.

Keywords: Mechanical Boom, Whale Algorithm, Finite Element Analysis, Structural Optimization.

1. Introduction

Mechanical boom is a kind of mechanical equipment commonly used in industrial production at present, the mechanical boom is used to support the container and other lifting weight, and make it change a certain lifting height. Mechanical boom can be tilted or telescopic movement, according to the structure of the type of truss boom, box-type lifting arm, et al. A good mechanical boom with good mechanical properties, is one of the important process devices for industrial production. The shape and size parameters of the mechanical boom are closely related to the quality of its workpiece, etc. Therefore, optimizing the process parameters is of great significance in obtaining high-quality mechanical boom workpieces [1]. Peng Fei et al. of China Electric Power Research Institute [2] studied the change of output force of crane boom based on three-dimensional modeling; Bai Yanqiang of Taiyuan University of Science and Technology [3] used Ansys to study the influence of three cross-sectional shapes on the maximum stress of crane telescopic boom; Cheng Yuanlu [4] of Nanhua University introduced the structure of the boom, the characteristics of the cross-sectional shape and the principle of telescopic operation, and theoretically deduced the formula for calculating the force of the boom in the process of operation; Wenbo Chen [1] in Hubei University of Technology, analyse the stiffness and structural optimize a 3-DOF robot by statics method; Xiaofeng Du [5] and others based on Solidworks modeling and Ansys Workbench for parametric analysis of three-axis robotic arm to meet the design requirements.

Whale Optimization Algorithm (WOA) is a novel population intelligent optimization algorithm proposed by Mirjalili et al. from Griffith University, Australia, in 2016, which simulates the principle of humpback whales feeding on prey using spiral bubble nets, and has the advantages including simple operation, fewer adjusted parameters, and strong ability to jump out of the local optimum [6].

As a novel system information processing method combining meta-inspired and species community behavior, it is able to solve the most complex optimization problems such as shifting, rotating, expanding and combining variants in unimodal and multimodal benchmark functions. Therefore, in this paper, the method of whale optimization algorithm is entered into the optimization of the structural parameters of the mechanical boom to design a 4-factor 4-level orthogonal test (L_{16}). Take the radius of the outer circle of the cross-section of mechanical boom, the shape of the cross-section, the distance of support points and the ratio of the cross-sectional area of the two ends of the boom as the structural parameter variables. The total deformation and equivalent force of the boom during the load-carrying deformation process were used as the evaluation indexes of load carrying capacity. Numerical simulation is carried out in Ansys finite element analysis software to provide theoretical basis for actual production.

2. Finite element simulation design

2.1. 3D and finite element modeling

In Solidworks software to establish the mechanical boom three-dimensional model parts, using three basic components for three-dimensional assembly, the material selection of structural steel, finite element simulation and analysis in Ansys Workbench software [7]. The structure of the assembly body is shown in Figure 1.

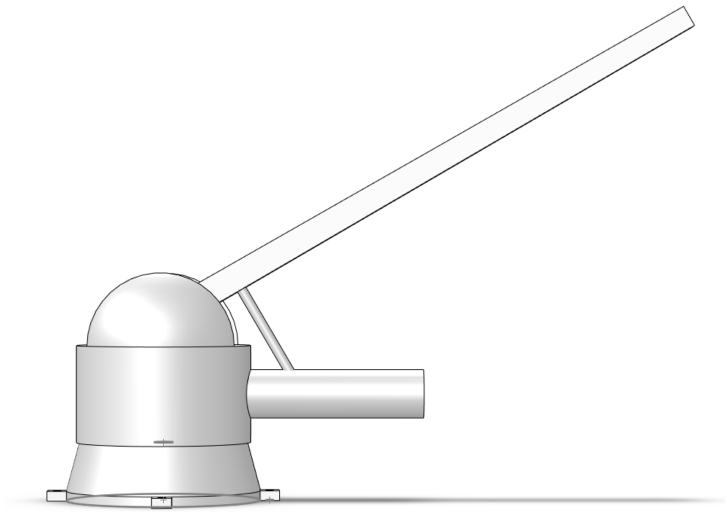

Figure 1. Finite Element Simulation Modeling from Solidworks

2.2. Invariant conditions

The mechanical boom assembly body has 2 degrees of freedom under ideal conditions, and the connecting rods of upper base and lower base can make rotational movements to turn the lifting arm horizontally. The hexagonal rotation axis of the upper base and the lifting arm can control the lifting arm to rotate up and down in small angles. In order to control the irrelevant variables, this simulation analysis uses the hexagonal fit to set the inclination angle of the lifting arm to the ground to 30°, and the total length of the mechanical boom to 600*mm*, and assumes that the same 1000N vertical downward force is applied at the end of the mechanical boom for each set of experiments. At the same time, the bottom surface of lower base, the support bar, and the hexagonal rotation axis of upper base were set as fixed supports, and the lifting arm was taken as the main research object to analyze its total deformation and equivalent force by finite element.

Using grid can better solve the structural analysis problem in ANSYS Workbench [8]. This finite element simulation uses mesh division, single experimental cell mesh edge length of 1.0 mm, to experiment 1, for example, a total of 10073 mesh division, nodes 19114, the results are shown in Figure 2.

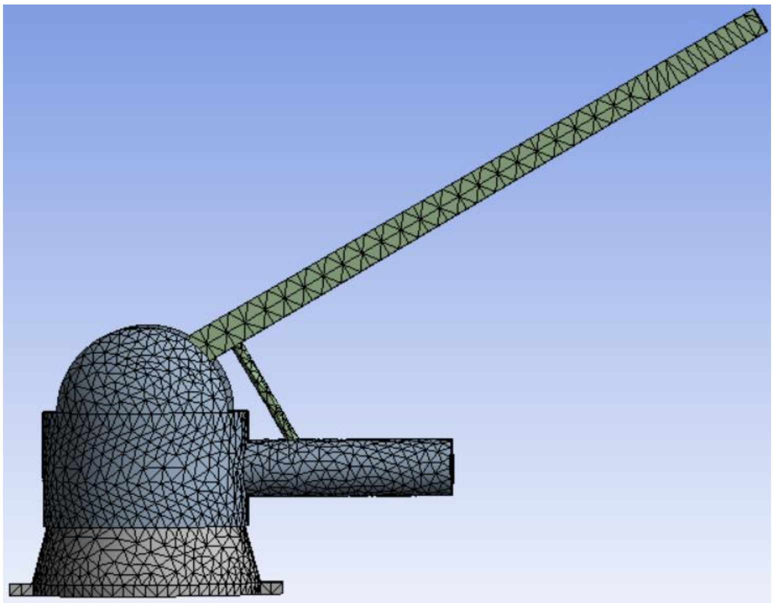

Figure 2. Ansys grid structure diagram

2.3. Orthogonal experimental design

In this study, the optimization scheme combining whale optimization algorithm and orthogonal experiment is used to design a 4-factor, 4-level orthogonal experiment table. The radius of the outer circle of the cross-section of the boom, the shape of the cross-section, the distance of the support point and the ratio of the cross-sectional area of the two ends of the boom were selected as the structural parameter variables. The parameter levels and the analysis results are shown in Table 1.

Table 1. Orthogonal experiment parameter design table

Number	Radius	Shape	Ratio	Support	Deformation	Stress
1	20	square	0.64	60	6.0872	227130000
2	20	triangle	0.76	90	10.0130	348740000
3	20	circle	0.88	120	1.6190	107010000
4	20	hexagon	1	150	1.7935	136360000
5	30	square	0.88	90	0.8991	61056000
6	30	triangle	1	60	1.9705	105360000
7	30	circle	0.64	120	0.4128	55164000
8	30	hexagon	0.76	150	0.4615	54843000
9	40	square	1	120	0.2345	35126000
10	40	triangle	0.88	150	0.4635	66886000
11	40	circle	0.76	60	0.1621	65578000
12	40	hexagon	0.64	90	0.2217	52843000
13	50	square	0.76	150	0.1051	36589000
14	50	triangle	0.64	120	0.2790	40459000
15	50	circle	1	90	0.0552	37098000
16	50	hexagon	0.88	60	0.0941	41090000

3. Whale Optimization Algorithm

3.1. SPSS regression analysis

This optimization experiment has four independent variables totaling outer circle radius, cross-section shape, support point distance and cross-sectional area ratio at both ends. There are deformation and equivalent stress totaling two dependent variables. The linear regression equation will be constructed by IBM SPSS software, and for the accuracy of the results, the power square ($x(1)^2$, $x(2)^2$, $x(3)^2$ ......), cubic ($x(1)^3$, $x(2)^3$, $x(3)^3$ ......) and product ($x(1)x(2)$, $x(1)x(3)$, $x(1)x(2)x(3)$, $x(1)x(2)x(4)$ ......) and other variable combination forms are also introduced. The linear regression equations were analyzed, ticking the Durbin-Watson and covariance diagnostics. The model summary charts were obtained as shown in Table 2.

Table 2. Model summary charts from IBM SPSS

Model Summary of Regression Analysis					
Model	R value	R square value	R square Adjusted	Errors in standardized estimates	Durbin Watson
1	0.985	0.970	0.555	1.80727	2.539

According to the results of the analysis, the R-squared value is close to 1, the model has the characteristics of fit, and the set variables are strongly correlated [9]. After the regression analysis and exclusion of non-variable factors, the regression equation was obtained as follows, *tau* is the amount of deformation, *omega* is the equivalent stress.

$$tau=15.609701-0.666902\times x(1)+0.021229\times x(3)+5.464594\times x(4)+0.000141\times x(1)^3+0.132303\times x(2)^2+0.068990\times x(1)\times x(2)-0.178756\times x(1)\times x(4)-2.151156\times x(2)\times x(4)+0.013316\times x(1)\times x(2)\times x(4)+0.001121\times x(1)\times x(3)\times x(4)-0.011314\times x(2)\times x(3)\times x(4)-0.175216\times x(2)^3-0.00000137\times x(3)^3-3.090808\times x(4)^3 \quad (1)$$

$$omega=557364031.532811-17646107.102868\times x(1)-44845.738271\times x(3)+160281839.177368\times x(4)+4508.336544\times x(1)^3+5668763.246800\times x(2)^2+2449478.931027\times x(1)\times x(2)-11454635.133101\times x(1)\times x(4)-41534034.675459\times x(2)\times x(4)+184578.695276\times x(1)\times x(2)\times x(4)+38663.266242\times x(1)\times x(3)\times x(4)-551847.632495\times x(2)\times x(3)\times x(4)-6455129.158599\times x(2)^3-25.087795\times x(3)^3+14870301.067259\times x(4)^3 \quad (2)$$

Where $x(1)$ is the radius of the outer circle of the cross-section of mechanical boom, $x(2)$ is the shape of the cross-section, $x(3)$ is the distance from the support point, $x(4)$ is the ratio of the cross-sectional area of the two ends of one boom.

3.2. Whale Optimization Algorithm

The whale optimization algorithm (WOA) is a novel meta-heuristic optimization algorithm proposed by observing the hunting behavior of humpback whale populations. In the WOA approach, the location of each humpback whale represents a viable solution. In ocean activities, humpback whales have a special hunting method, and this foraging behavior is called bubble net predation strategy [10]. The hunting behavior is shown in Figure 3.

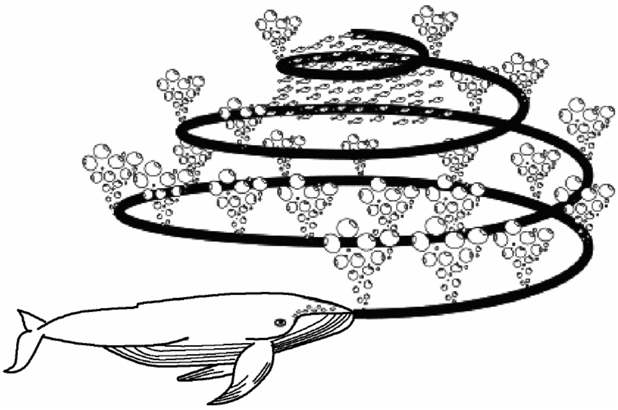

Figure 3. Hunting behavior of the whale

(1) Surrounding the prey target

Humpbacks encircle their prey, for instance, fishes, when they hunt. To describe this behavior, a mathematical model is proposed by Mirjalili, and it is shown as following.

$$D = \left| CX^*(t) - X(t) \right| \tag{3}$$

$$X(t+1) = X^*(t) - AD \tag{4}$$

In these equations, t denotes the current number of the iterations, A and C denotes the coefficients, $X^*(t)$ denotes the best whale position vector so far, $X(t)$ denotes the current whale position vector, A and C from Eq. (3), Eq. (4)

$$A = 2ar_1 - a \tag{5}$$

$$c = 2r_2 \tag{6}$$

Where, r_1 and r_2 is a random number in (0,1), the value of a which decreases linearly from 2 to 0, t denotes the current number of iterations, and $T_{\max}$ is the maximum number of iterations.

$$a = 2 - 2t / T_{\max} \tag{7}$$

(2) Hunting behavior

Based on the hunting behavior of humpback whale, it swims to the prey with spiral motion, so the mathematical model of the hunting behavior can be presented and the formula is as following.

$$X(t+1) = X^*(t) + D_p e^{bl} \cos(2\pi l) \tag{8}$$

In this equation, $D_p = \left| X^*(t) - X(t) \right|$ denotes the distance between the whale and their prey, $X^*(t)$ denotes the best position vector so far, b is a constant which defines the shape of the spiral, in the same time l is a random number in (-1,1).

It should be noticed that whales swim towards their prey in a spiral shape while simultaneously contracting their envelope. Therefore, in this simultaneous behavioral model, it is assumed that there is a probability P_i of choosing the contracting envelope mechanism and a probability $1 - P_i$ of choosing the spiral model to timely update the position of the whale, which is mathematically modeled as follows.

$$X(t+1) = \begin{cases} X^*(t) - AD & p < P_i \\ X^*(t) + D_p e^{bl} \cos(2\pi l) & p \ge P_i \end{cases} \tag{9}$$

When attacking the prey, the mathematical model sets a decreasing value a close to the prey, so that the range of A fluctuation decreases with a. In the iterative process when the value of a decline from 2 to 0, A is the random value within $[-a, a]$. In the situation the value of A within the [-1, 1], the next position of the whale can change to any position between the whale’s current position and the position of the prey. The algorithm is set at that time $A < 1$, the whale launched an attack on the prey.

(3) Search for the prey

When searching for prey, the mathematical model is as follows.

$$D = \left| CX_{rand} - X(t) \right| \tag{10}$$

$$X(t+1) = X_{rand} - AD \tag{11}$$

In these equations, X_{rand} is a whale position vector which is randomly selected. When the algorithm is set $A \geq 1$, a search agent is randomly selected to update the position of other whales according to the randomly selected whale position, forcing the whales to deviate from the prey, so as to find a more suitable prey to pursue. This method can strengthen the exploration ability of the whale algorithm. Therefore, the WOA can carry out a global search.

3.3. Matlab Algorithm Implementation

The regression equation obtained through SPSS software is adjusted by the algorithm, adding the defined domain interval, substituted into the whale optimization algorithm. And the results are finally analyzed and charted through 200 random experiments, as shown in Figure 4.

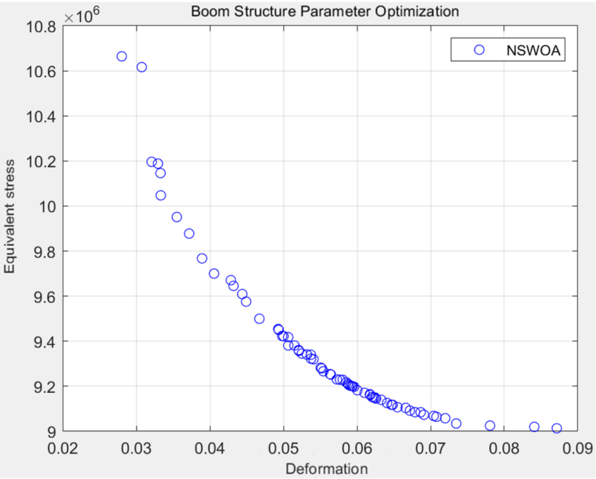

Figure 4. Parameter optimization analysis results

4. Conclusion

The optimal solution is found by whale optimization algorithm. The optimal combination of mechanical boom parameters is obtained as the outer circle radius is 38.9*mm*, the cross-section shape is circular, the distance of the support point is 66.12*mm*, and the cross-sectional area ratio of the two ends of the boom is 0.94. In this case the deformation and the equivalent force of the mechanical boom when subjected to a vertical downward force of 1000N are minimized, and the structure is optimal. At this time, the deformation is 0.035*mm* and the equivalent force is 353500000*pa*, which proves that the mechanical boom structure size is optimized.

In this process of research, the application of multi-domain simulation software skills including modeling, structural mechanics analysis, data analysis, and algorithms is taken. During the design and modeling of the mechanical boom, Solidworks and Ansys analysis are used for three dimensional design and presentation. In the analysis of the structural parameters of the mechanical boom, the combination of SPSS regression analysis and whale optimization algorithm is used to optimize the structural parameters by designing orthogonal tests. At the same time, in the whole experiment design, the application of orthogonal experiment method greatly reduces the workload, and the experimental law is found by using less experiment times under the condition of limited modeling resources. The optimization experiment of the mechanical boom provides reference basis for actual production. The method and systematic design used in this experiment can provide reference for other mechanical structure experiments.

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