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Integral Elastic Centralizer based on Gray Correlation and Multi-island Genetic Algorithm Optimization of Structural Parameters Integral

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Abstract

Based on grey correlation and RBF neural network-multi-island genetic algorithm, combined with finite element simulation to optimize the structural parameters of the monolithic elastic righting device to improve its reset force performance. The righting device is a circumferentially symmetric structure, and the model is simplified to a single bow piece model of 1/6. The bow piece chord length, width, and thickness are selected as the key parameters, and a three-factor, four-level orthogonal experiment is conducted to analyze the influence of each parameter with the help of the gray correlation degree method. The Latin supergroup square sampling method was used to randomly sample the influence factors to obtain reasonable training samples and validation data. The chord length, width, and thickness are taken as input parameters, the reset force value is taken as output, the RBF neural network-multi-island genetic algorithm optimization model is constructed, and the grey correlation degree is used as the weight to guide the optimization direction. After optimization, the optimal parameter combinations of chord length 231 mm, width 44 mm, and thickness 4.6 mm were obtained, at which time the predicted value of reset force reached 19760.39 N. Simulation and validation results show that the relative error between simulated and predicted values is only 1.1%, and the reset force is improved by 50.76% compared with that before optimization, which fully verifies the feasibility of the optimization model.

Keywords

Integral Elastic Centralizer, Reset Force, Grey Correlation, Neural Network, Multi-Island Genetic Algorithm, Structure Optimization.

1. Introduction

The casing holder is an important technical measure to improve casing centering in oil drilling engineering [1-2]. Its main function is to ensure the accurate positioning of casing in the borehole and prevent direct contact between casing and well wall, thus reducing the risk of abrasion and jamming, which has a significant impact on the cementing quality [3-7]. According to the structural characteristics, correctors are mainly divided into two categories: elastic and rigid correctors [8]. Due to its one-piece molding design, the integral elastic corrector has the advantages of a larger reset force, smaller start-up force, and stronger adaptability than the traditional elastic casing corrector, so it is widely used in engineering practice [9-10]. The reset force, as the core index of the performance of the integral elastic straightener, has a direct impact on the centering of the casing in the borehole. If the reset force is insufficient, the casing may contact with the well wall due to excessive offset, resulting in uneven distribution of cementing rings, increased wear of casing, and even leading to jamming accidents. Therefore, it is of great significance to improve the reset force performance of the holder.

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In the field of research on the reset force performance of the righting device, many scholars have carried out a lot of research work. Xiao Xinyu et al [11] verified through field tests that Centek's new monolithic elastic righting device, which adopts advanced manufacturing process and quenching technology and adds rare element boron in the material, can significantly improve the reset force, which lays a material foundation for the subsequent structural optimization. Liu Ming et al [12] combined with the structural characteristics of the integral type righting device, established the bow piece design calculation theory, and simulated and verified the optimization of the bow piece structure and the reset force using ABAQUS finite element analysis method. Liu Xinzhe et al [13] systematically studied the influence law of bow piece chord length, wall thickness and width on the reset force and strain energy density of the righting device based on the response surface method. Lu Huatao et al [14]. Based on the CFD fluid simulation method, the shape of the righting wing of the drill-following righter was optimized and designed. Jiao Liming et al [15]. Workbench and Adams software were used to analyze and simulate the mechanics of the new adjustable righting device. Zou Zhengwei et al [16]. Through the flow field simulation, the influence of the height of the righting device and the height of the righting prong on the fluid attenuation, and the influence of the cross-section of the righting prong on the overflow characteristics were analyzed, and the relevant geometric parameters were finally determined, which realized the synergistic optimization of the hydrodynamic performance and the structural design. In terms of engineering time, Xu Xing et al [17]. Through systematic generalization and simulation analysis, the selection and placement scheme of the righting device for different well conditions and processes is proposed, which provides an important reference for engineering practice. Hu Haobo et al [18]. Based on the longitudinal and transverse bending beam and soft rod model, the influence of the correcting device on the casing downward load in spoon wells and wells with large slope is studied, and the drag reduction effect of different combinations of correcting devices is analyzed. Liu Xianfu et al [19]. analyzed the causes of fracture of downhole correctors and proposed to optimize the outer diameter of correctors to reduce the risk of fracture. The above researches have made significant progress in the innovation of material, structure optimization, and engineering application of the righting device, but the existing optimization methods have problems such as high computational cost and low efficiency of multi-parameter optimization.

In order to realize the multi-parameter co-optimization of the integral righting device structure, enhance the optimization efficiency, and further improve the reset force performance of the integral righting device and reduce the computational cost, this paper introduces the co-optimization method based on the RBF neural network agent model and multi-island genetic algorithm, and uses the degree of correlation as the weight to guide the multi-island genetic algorithm to realize the optimization of the parameter combinations and adopts the finite element simulation analysis to verify the accuracy of the optimization method. The finite element simulation analysis is used to verify the accuracy of the optimization method. In order to achieve the synergistic optimization of three key structural parameters, namely, the string length, width and thickness of the integral elastic corrective device, the algorithm provides a new way for the optimization of the corrective device structure.

2. Integral Elastic Corrective Device Finite Element Simulation and its Result Analysis

2.1. Basic Structure and Parameters

In this study, an integral elastic corrective device of 139.7 mm (5½ in.) × 215.9 mm (8½ in.) size was used as the object of study. Its main parameters are: wall thickness of 4 mm, bow piece width of 40 mm, bow piece chord length of 238 mm, round hoop length of 55 mm, fillet radius

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of 5 mm, 60Si2Mn material, curved cross-section, and the number of bow pieces is 6 pieces. The specific structure is shown in Figure 1.

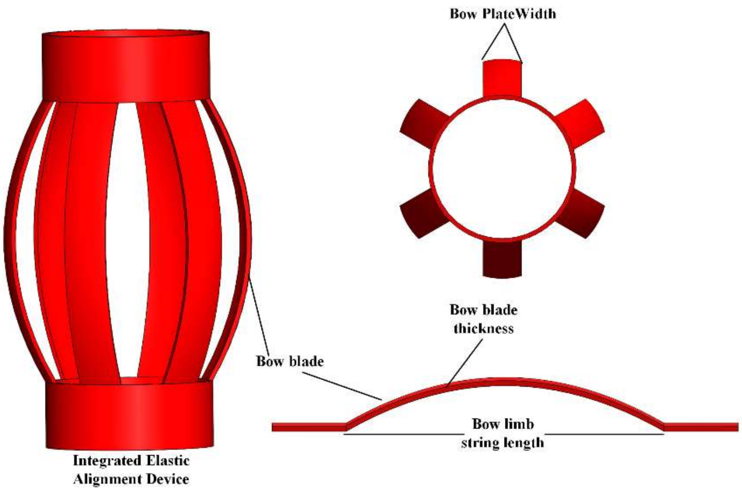
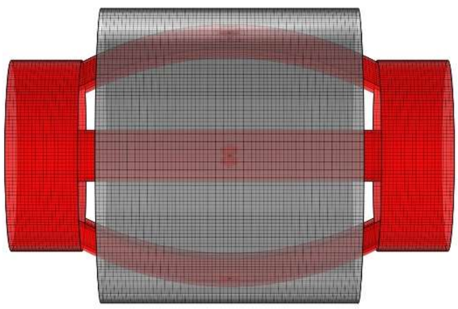


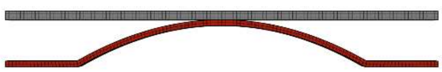
Figure 1. Integral Elastic Retainer Structure

2.2. Finite Element Modeling

The structure of the integral elastomeric righting device is circumferentially symmetrical, and its outer diameter is smaller than or equal to the size of the borehole. Ideally, under the working condition, each bow piece is subjected to the same squeezing force after entering the well, i.e., the reset force generated by each bow piece is of equal magnitude. In order to improve the finite element simulation accuracy and reduce the calculation volume, 1/6 model is adopted for simulation analysis, i.e., a single bow piece model of the corrector is modeled to complete the simulation analysis. The finite element model is shown in Figure 2.



a.Enabler-well wall model



b. Arch-wall model

Figure 2. finite element model

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The formula for the reset force of a single bow piece is given by $F_N = \frac{4Ebh^3}{L^3} D$, Where E is the modulus of elasticity of the bow piece material, MPa; b is the width of the bow piece, mm; h is the thickness of the bow piece, mm; L is the string length of the bow piece, mm; D is the distance of the bow piece contracted by extrusion, mm; FN is the reset force, N.

2.3. Boundary Conditions and Load Settings

Before finite element simulation and analysis, the following constraints and loads need to be set:

(1) Contact: contact constraints need to be set between the bow piece and the well wall and casing in order to facilitate the simulation of the extrusion between the well wall-bow piece-casing.

(2) Fixed constraints: the ring hoop part is kept close to the casing surface, its radial freedom is fixedly constrained, and the lateral direction is kept free; and fixed constraints are applied to the casing as a whole.

(3) Radial compression load: radial compression displacement is applied to the retainer through the well wall to simulate the actual compression deformation process, and quasi-static compression is used to apply the displacement load in steps until a 67% deviation gap ratio is reached, i.e., the maximum radial displacement is 12.54 mm [20].

The above boundary conditions and load settings ensure that the model can accurately reflect the mechanical behavior under actual working conditions, and the specific constraints are shown in Figure 3.

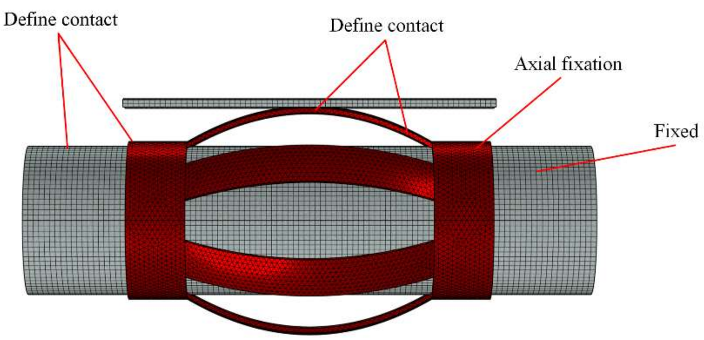

Figure 3. restrictive condition

2.4. Finite Element Simulation Analysis

Through the finite element software simulation and analysis, the finite element simulation results of the bow piece reset force are shown in Figure 4.

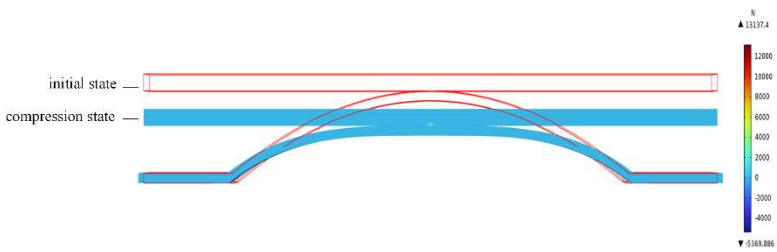

Figure 4. Reset force finite element analysis results

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According to the actual engineering standard, the design value of the reset force of the bow plate of this type of corrective device is 4168.56 N. The finite element simulation analysis shows that when the bow plate is compressed to 67% of the deviation gap ratio, the reset force reaches 13137.4 N, which is far more than the design requirement. Experimentally measured reset force is 13254.75 N, and the error with the simulation result is only 0.08%, much lower than the allowable error of 5%, so it can be seen that the finite element analysis is reliable.

3. Orthogonal Experiment Program and Evaluation Index

The string length (L), width (b), and thickness (h) of the bow blade were selected as the main influencing factors, and a three-factor, four-level orthogonal test table was designed to evaluate the bow blade reset force (FN) of the integral elastic righting device. The string length, width, and thickness of the bow blade were selected within a certain range according to the above mentioned structural parameters of the 139.7 mm (5½ inches) × 215.9 mm (8½ inches) size of the Integral Elastic Retainer [13]. The orthogonal test factors and levels are shown in Table 1.

Table 1. Orthogonal test factors and levels

level (of achievement etc)	Test Factor		
	String length of bow blade	Width of bow blade	Bow Plate Thickness
	L/mm	b/mm	h/mm
1	230	34	3.6
2	238	38	4.0
3	246	42	4.4
4	250	44	4.6

Based on the test factor and level design in Table 1, 16 groups of parameter combinations were constructed, and the corresponding results were obtained by simulating and analyzing the reset force of the righting device under each group of parameter combinations. The orthogonal test program and results are shown in Table 2.

Table 2. Orthogonal test protocol and results

serial number	L/mm	b/mm	h/mm	FN/N
1	230	34	3.6	8992.06
2	230	38	4.0	13196.43
3	230	42	4.4	17722.56
4	230	44	4.6	20295.20
5	238	34	4.0	11292.47
6	238	38	3.6	10004.28
7	238	42	4.6	18339.76
8	238	44	4.4	17456.34
9	246	34	4.4	12772.08
10	246	38	4.6	15603.06
11	246	42	3.6	9664.57
12	246	44	4.0	13210.08
13	250	34	4.6	13809.48
14	250	38	4.4	13973.21
15	250	42	4.0	12309.77
16	250	44	3.6	9755.38

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4. Gray Correlation Analysis and Latin Hypercube Sampling

4.1. Gray Correlation Analysis

Gray correlation analysis is a data analysis method based on gray system theory for assessing the degree of correlation between factors in a system. It judges the correlation between factors by comparing the change trends between them, and the more similar the change trends are, the higher the degree of correlation is. In the performance evaluation system of the integral elastic righting device, the reset force (FN), as a key performance index, is selected as the reference sequence (parent sequence), and the three main structural parameters affecting the reset force - the bow blade chord length (L), the bow blade width (b), and the bow blade thickness (h) - are taken as the comparison sequence (sub-sequence). The gray correlation degree analysis of the reset force performance of the integral elastic corrective device was performed as follows.

For the first time, the raw data obtained from the orthogonal experiments are initialized to eliminate the differences in magnitude and order of magnitude between the series, and the initialization formula is $x_i'(k)=\frac{x_i(k)}{x_i(1)}$, where $x_i(1)$ is the first value of the first sequence, k=1,2,3,...,n. The initialized data are shown in Table 3.

Table 3. Initialized data for the three factors and the reset force

serial number	L/mm	b/mm	h/mm	FN/N
1	1	1	1	1
2	1	1.12	1.11	1.47
3	1	1.24	1.22	1.97
4	1	1.29	1.28	2.26
5	1.03	1	1.11	1.26
6	1.03	1.12	1	1.11
7	1.03	1.24	1.28	2.04
8	1.03	1.29	1.22	1.94
9	1.07	1	1.22	1.42
10	1.07	1.12	1.28	1.74
11	1.07	1.24	1	1.07
12	1.07	1.29	1.11	1.47
13	1.09	1	1.28	1.54
14	1.09	1.12	1.22	1.55
15	1.09	1.24	1.11	1.37
16	1.09	1.29	1	1.08

The correlation coefficient is the relative difference between the comparison sequence curve and the reference sequence curve at each point, for the kth number in the sequence with and , the formula for the correlation coefficient is shown in equation (1).

$$\gamma_i(k)=\frac{min_i min_k|\ x_0(k)-x_i(k)|+\rho max_i maxk|\ x_0(k)-x_i(k)|}{|\ x_0(k)-x_i(k)|+\rho max_i max_k|\ x_0(k)-x_i(k)|} \tag{1}$$

where $|x_0(k)-x_i(k)|$ is the difference at each moment k; $min_i min_k | x_0(k)-x_i(k)|$ denotes the global minimum difference; $max_i maxk| x_0(k)-x_i(k)|$ denotes the global maximum difference; and 5 is the resolution factor, usually taken as ρ = 0.5.

Gray correlation is the average of the gray correlation coefficients for the

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\gamma_i(k) \tag{2}$$

The correlation coefficients as well as the correlation degrees of the three comparative and reference sequences were calculated according to equations (1) and (2). The calculation results are shown in Tables 4 and 5.

Table 4. Correlation coefficients between the three factors and resilience

serial number	L/mm	b/mm	h/mm
1	1.000	1.000	1.000
2	0.790	0.850	0.830
3	0.680	0.740	0.720
4	0.630	0.690	0.670
5	0.770	0.820	0.800
6	0.830	0.880	0.860
7	0.650	0.710	0.690
8	0.670	0.730	0.710
9	0.730	0.780	0.760
10	0.690	0.750	0.73
11	0.840	0.890	0.870
12	0.790	0.850	0.830
13	0.710	0.770	0.750
14	0.720	0.780	0.760
15	0.760	0.810	0.790
16	0.820	0.870	0.850

Table 5. Gray correlation analysis results

Structural parameters	relatedness	rankings
L	0.75	3
b	0.82	1
h	0.78	2

According to Table 5, the gray correlation ranking: width > thickness > chord length. The larger the gray correlation, the greater the correlation between the corresponding parameter and the reset force of the integral bullet retainer, and the greater its influence on the reset force production, indicating that the width is dominant in influencing the size of the reset force, and its contribution to the reset force is the largest. In parameter optimization, in order to obtain a larger reset force, the focus should be on changing the width and then adjusting the appropriate thickness and chord length to improve the reset force [21]. Therefore, it is proposed to assign the correlation degree as the optimization weight to guide the optimization direction of the multi-island genetic algorithm during the optimization process, in order to find a suitable parameter combination to further improve the reset force performance.

4.2. Latin Hypercube Sampling

To ensure that the samples are sufficiently dispersed and the accuracy of the subsequent optimization, Latin hypercubic sampling was used to randomly sample the string length of the bow blade in the interval [230mm,250mm], the width of the bow blade in the interval [34mm, 44mm], and the thickness of the bow blade in the interval [3.6mm, 4.6mm]. The total number of samples was set to 50, and the sampling data are shown in Figure 5.

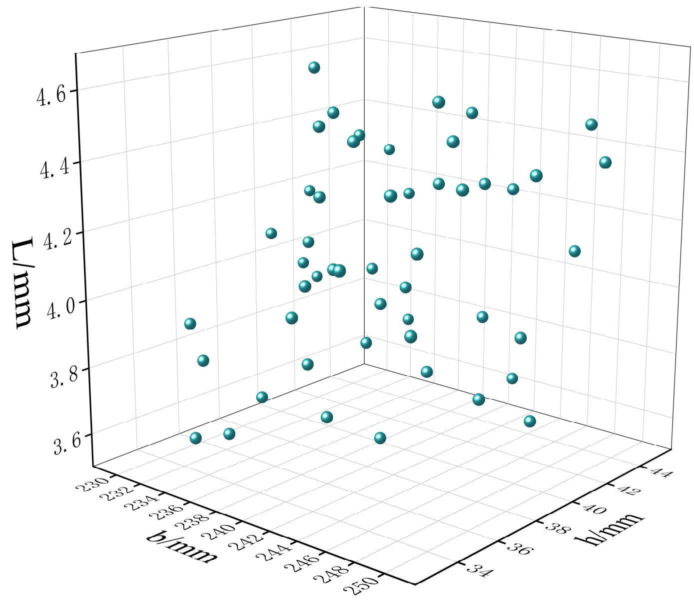

Figure 5. Latin Hypercube Sample Data

5. Optimization of Structural Parameters based on RBF Neural Network Model-Multi-Island Genetic Algorithm

5.1. RBF Neural Network Model Construction

RBF neural network model is an approximation model of three-layer neural network with Radial Basis Function (RBF) as the activation function, which generates a local response by calculating the distance between the inputs and the center to achieve fitting and prediction of nonlinear data, with a strong generalization ability [22-24].The structure of the RBF neural network is shown in Figure 6, where, X1 ,...,XN are the input values, Y1,. .Y2 are the output values and N is the number of input and output data.

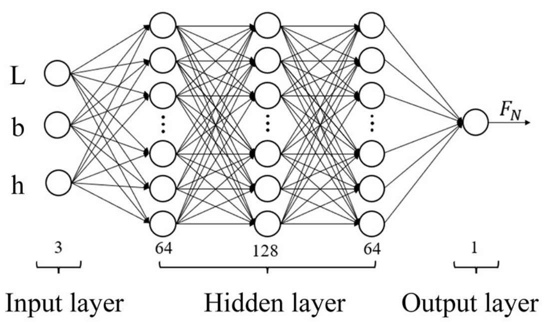

Figure 6. RBF neural network structure

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In this paper, the RBF neural network is constructed by taking the chord length (L), width (b) and thickness (h) as inputs, and the reset force (FN) of the integral elastic righting device as output. Through Latin hypercubic sampling and then re-simulation calculation, 40 groups of data are obtained as training samples, and the other 10 groups are used as test data, so as to construct the RBF neural network with the reset force as the optimization objective. The model constraints are as follows.

$$s.t.\begin{cases} 230mm \le L \le 150mm \\ 34mm \le b \le 44mm \\ 3.6mm \le h \le 4.6mm \end{cases} \tag{3}$$

5.2. RBF Neural Network Model Prediction Results and Analysis

The reliability of the RBF neural network model was measured by comparing the predicted values output from the network model and the corresponding simulated values from the 10 sets of validation data, and the relative error was used to measure the reliability of the RBF neural network model. The distribution of relative errors between predicted and simulated values is shown in Figure 7. The validation results show that the maximum relative error is 0.23% and the minimum error is 0.03%, which are within the normal error range of 5%, thus it can be seen that the neural network model can predict the maximum reset force value of the bow piece more reliably.

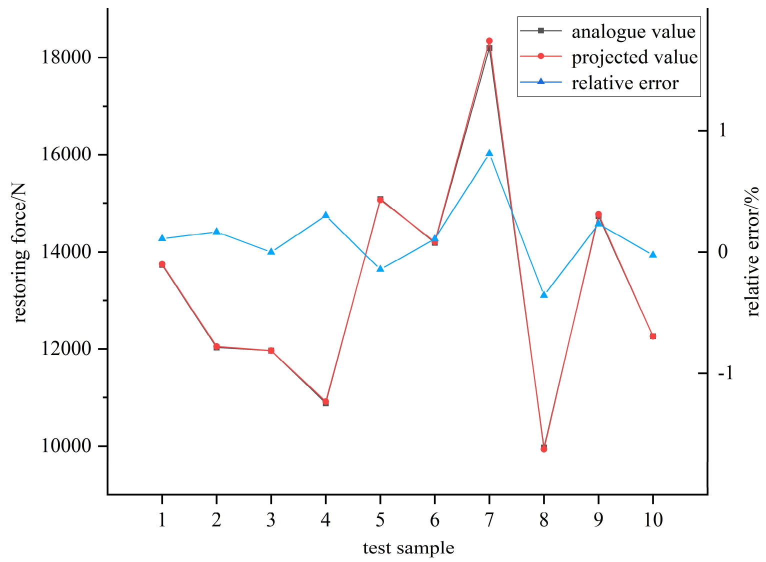

Figure 7. Relative error analysis of simulated and predicted values

5.3. Optimization Results of Parameters based on Multi-Island Genetic Algorithm

Multi-island genetic algorithm is a distributed optimization algorithm that achieves information exchange between islands through a multi-island framework and a population migration mechanism, so as to maintain the population diversity and improve the global search ability and convergence performance [25]. In this paper, we combine the grey correlation degree as the optimization weight to guide the optimization direction of the multi-island genetic algorithm, which is based on the above neural network for objective optimization. The algorithm sets the number of populations as 10, the number of islands as 10, and the number of genetic generations as 10, totaling 1000 iterations. Optimization of structural parameter combinations was carried out in the agent model, and the optimal parameter combinations and

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their corresponding reset force prediction values were obtained through iterative optimization, and the specific results haode shown in Table 6.

Table 6. Optimal parameter combinations and prediction results

String length of bow blade /mm	Width of bow blade /mm	Bow Plate Thickness /mm	restoring force/N
231.14	43.89	4.58	19760.39

6. Finite Element Simulation Verification

In order to meet the actual production requirements and facilitate the simulation verification, this study is based on the calculation results of the optimization algorithm, the optimal parameter combinations are adjusted to integer values, i.e., the chord length is 231 mm, the width is 44 mm, and the thickness is 4.6 mm. Based on the above parameter combinations, the finite element model is adjusted, and the simulation analysis of the reset force is carried out. The simulation results under the optimal parameter combination are shown in Figure 8.

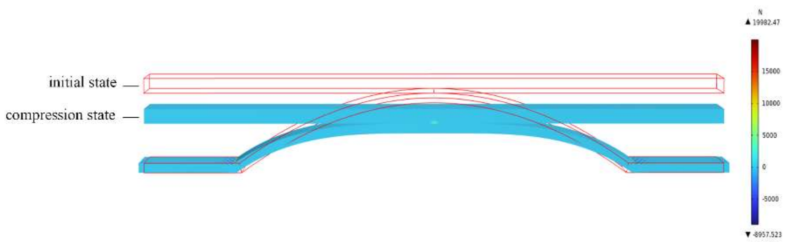

Figure 8. Simulation results of optimal parameter combination

As shown in Figure 8, the maximum reset force of the integral elastic righting device optimized by grey correlation analysis and genetic algorithm reaches 19982.47N, which is less than 5% compared with the algorithm predicted value of 19760.39N, and the error is within the reasonable range. Compared with the initial design before optimization, the reset force increases from 13254.75N to 19982.47N, an increase of 50.76%, effectively proving the feasibility of the optimization method.

7. Conclusion

In this paper, the optimal parameter combinations of string length, width and thickness of the bow piece are obtained through algorithmic optimization, taking the reset force of the integral elastic armature as the optimization objective. The main conclusions are as follows:

(1) The orthogonal experimental method and gray correlation analysis are used, combined with finite element simulation, to clarify the degree of correlation between each structural parameter and the performance of reset force. The results show that the width has the greatest influence on the reset force, followed by the thickness and chord length. Therefore, the parameter optimization should give priority to adjusting the width, and then adjust the thickness and chord length appropriately, and this optimization strategy can effectively improve the reset performance of the integral elastic righting device.

(2) Establish the model based on RBF neural network and multi-island genetic algorithm, and use the gray correlation degree as the weight coefficient to guide the direction of optimization, and obtain the optimal parameter combinations of the bow piece of the integral elastic righting device: the string length is 231 mm, the width is 44 mm, and the thickness is 4.6 mm, and the predicted value of the reset force at this time is 19760.39N.

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(3) The simulation analysis of the optimal parameter combination shows that the error between the simulated and predicted reset force is only 1.1%, which is within a reasonable range, proving the effectiveness of the optimization method, and the reset force is improved by 50.76% compared with the pre-optimization one, which effectively reduces the computation time and the consumption of computational resources, and improves the optimization efficiency.

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