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Lightweight Design of Hinged Beam Structure Based on Agent Model

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Abstract. This paper presents an optimization method based on the Kriging and multi-objective genetic algorithm. Firstly, taking the hinged beam structure of the cubic diamond press as the design object, the optimization design mathematical model is established with the quality as the objective function, the stress peak and displacement peak as the constraint conditions. Secondly, in combination with SolidWorks and ANSYS Workbench, parametric modeling analysis was conducted to obtain a large number of sample points sparing less time, and the agent model constructed by Kriging was trained and verified. Finally, taking advantage of global search of the multi-objective genetic algorithm, the lightweight design is realized and the quality of the hinge beam structure is effectively reduced, which would be a guiding significance for the lightweight design of other mechanical parts.

Keywords. Hinge beam structure, lightweight, finite element analysis, sensitivity analysis, the agent model

1. Introduction

With the rapid development of industry and the promotion of national policies in recent years, the market demand for diamond products is increasing, and the production process and application equipment of diamond manufacturing are constantly optimized and improved. In order to obtain higher yield and synthesize diamond of higher grade and larger grain, the large-scale step of the cubic diamond press is still advancing[1]. The large-scale mechanical structure also means the improvement of structural design rationality, structural safety and reliability. so the lightweight design of the hinge beam structure of the cubic diamond press is of great significance [2].

Agent model technology has been widely used in the optimization of engineering problems, and many scholars have carried out research on the optimization of agent model. Qingping Zhang[3] used multi-objective genetic algorithm to optimize the bed structure. Kang Di[4] obtained the optimal solution by using non-dominated sorting genetic algorithm on the basis of Kriging agent model. Di Trapani Fabio[5] proposed a new specific optimization framework for minimization problems and defined a new

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genetic algorithm, which can solve reconstruction optimization problems. Zhang Jian [6] adopted ant colony algorithm to optimize rail size and proposed a lightweight optimization idea based on TC4 titanium alloy frame structure design. All these studies provide ideas for the optimization of hinged beam structure.

In this method, firstly, the correlation analysis is carried out, and the structural parameters that have a greater impact on the output response are selected as the input variables, and the mass, volume stress peak and displacement peak of the hinge beam are taken as the output variables to establish a mathematical optimization model. Secondly, the optimal space design method is used to obtain the initial sample points, and parametric modeling was carried out with the SolidWorks and ANSYS Workbench, to obtain multiple groups of sample points. Finally, sample points were used to fit the Kriging agent model and verify its accuracy. After the fitting accuracy of the agent model reached the standard, multi-objective genetic algorithm was used to conduct global search and iterate to pursue the optimal design. Finally, the lightweight design of the hinged beam structure was completed.

2. Correlation analysis

Thirty groups of sample combination points were obtained through eight design variables. Correlation analysis was conducted on each design variable according to the input and output of the thirty groups of sample points to obtain the degree of influence of each design variable on the output. The correlation histogram is shown in Figure 1. Correlation analysis is based on Spearman's Rank Correlation statistical method. It calculates correlation coefficients by sorting the values of sample variables. It is applicable to the correlation between variables with nonlinear monotone change function relationship. The closer the correlation coefficient is to 1, the stronger the quadratic correlation is.

Figure 2. shows the correlation matrix between input and output. The darker the color in the matrix, the higher the correlation between the two parameters. According to the calculated correlation coefficient, the lug thickness (x_1, x_2), inner diameter(x_3), inner wall depth (x_4)and the lug length（x5）of the hinge beam are selected as the design variables of the lightweight of the hinge beam after filtering.

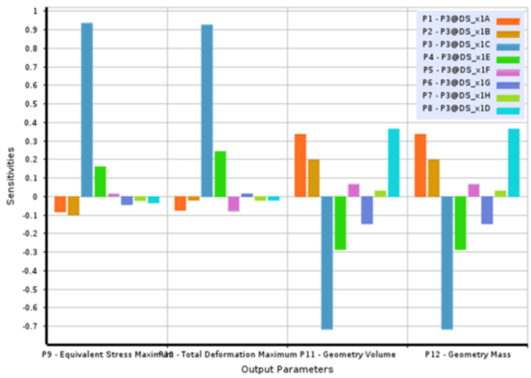


Figure 1. Sensitivity histogram.

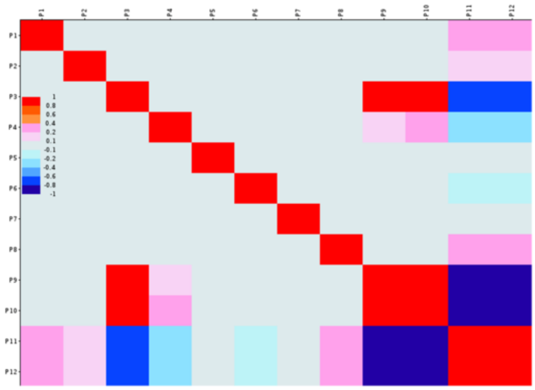
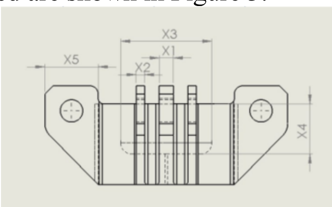


Figure 2. Correlation matrix diagram.

3. Establishment of mathematical model for structural optimization of hinged beam

Hinge beam structure is one of the key components of the cubic diamond press, which is of great significance to its lightweight. The optimization model of hinged beam structure is established as follows[7].

Firstly, according to the correlation analysis results, the final design variables selected are shown in Figure 3.



X1	Hinge beam lug thickness 1 (large)
X2	Hinge beam lug thickness 2 (small)
X3	Inner diameter of hinge beam
X4	Inner wall depth of hinge beam
X5	Lug length of hinge beam

Figure 3. Hinge beam structure and its design variables.

Secondly, the objective function of hinge beam lightweight design is to minimize the mass of hinge beam on the premise of satisfying its performance. Therefore, the quality of the hinged beam is taken as the objective function:

$$\mathrm{minf(x)} = \mathrm{f}(x) = \mathrm{m}(x_1, x_2, x_3, x_4, x_5) \tag{1}$$

Finally, the strength and stiffness of hinged beam structure will change with the size of each part, so the strength and stiffness should be checked, that is, the strength condition should meet the stress constraint, and the stiffness condition should meet the displacement constraint. Most domestic manufacturers use 35CrMo as the material for casting hinge beams. At room temperature, its elastic modulus $E = 200000\mathrm{MPa}$, Poisson's ratio $\mu = 0.3$, yield strength $\sigma_s = 730\mathrm{MPa}$ and allowable displacementδ=1.5mm, and its safety factor is 1.5, then the stress constraint function and displacement constraint function of the material are respectively:

$$g_1(x) = \sigma_x - \frac{[\sigma_S]}{1.5} \leq 0 \tag{2}$$

$$g_2(x) = \delta_x - [\delta] \leq 0 \tag{3}$$

Boundary constraints are the value range of design variables. According to the size standard, the value range of each design variable is:

$$\begin{cases} 80 \leq x_1 \leq 120 \\ 40 \leq x_2 \leq 80 \\ 500 \leq x_3 \leq 800 \\ 300 \leq x_4 \leq 420 \\ 320 \leq x_5 \leq 440 \end{cases} \tag{4}$$

4. FEA of hinge beam

Through the static analysis of the hinge beam structure by ANSYS finite element analysis software, the stress distribution of the hinge beam structure in general state can be obtained[8~11]. The linear tetrahedral quadratic isoparametric element is used to divide the finite element mesh because it has a good effect on boundary fitting. The finite element model of the hinge beam is divided into 54588 elements and 95367 nodes. A full constraint was applied to the lug through hole of the hinged beam, and a working oil pressure of 100MPa was applied to the beam wall.

The hinged beam model is solved and the displacement and stress cloud maps of the hinged beam are obtained, as shown in Figure 4. The maximum displacement of the hinged beam is distributed at the center of the inner bottom of the beam, which is 0.67059mm, and the maximum stress is located at the lug through hole of the hinged beam, which is 457.62MPa. The stress at the transition fillet at the bottom of the hinge beam is about 391.98MPa. In practical production, the fracture of hinge beam often occurs at the bottom transition fillet and lug through hole. The finite element analysis results are consistent with the actual situation, which verifies the rationality of the finite analysis results.

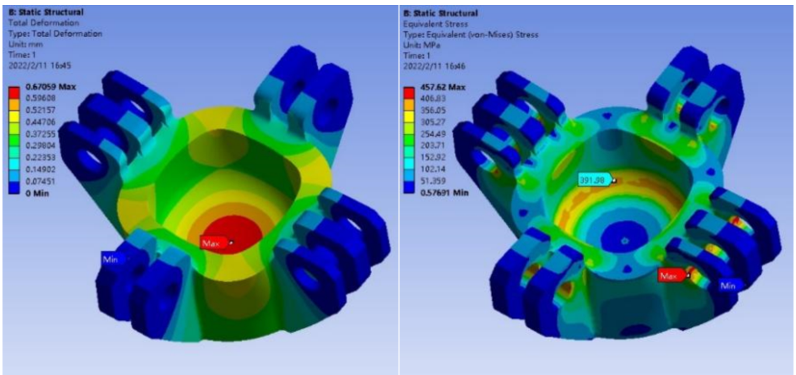


Figure 4. Displacement and stress cloud of hinge beam.

5. Agent model optimization

5.1. Design of experiment

In this paper, the optimal space filling design sampling method is adopted to carry out reasonable sampling in the feasible region composed of the value range of design variables[12]. optimal space filling sampling method(OSF), with its maximum interpoint distance and more uniform point distribution, solves the extremum problem more effectively, provides better coverage for design space, and ensures the filling of design space.

The SolidWorks parametric design combined with ANSYS Workbench finite element analysis, finally obtained 130 groups of design variables and quality, stress peak and displacement peak output sample points.

Table 1. Sample points obtained in DOE experiment.

Design point	X1	X2	X3	X4	X5	P9(MPa)	P10(mm)	P11(mm^3)	P12(KG)
1	90.2	74.6	564.5	407.4	411.8	388.78	0.59951	4.9934E+08	3919.8
2	103.4	47.8	789.5	324.6	353	775.72	1.2642	4.138E+08	3248.3
3	85.8	78.6	558.5	349.8	357.8	340.2	0.47432	4.9003E+08	3846.7
…….	…….	…….	…….	…….	…….	…….	……	…….	…….
130	119.76	76.6	793.01	303.38	418.2	595.59	0.9241	5.0039E+08	3928

5.2. Establishment of agent model

Kriging agent model is a kind of interpolation-free estimation model, which can not only accurately and quickly predict the response value of the unknown point, but also measure the model's inaccuracy performance[13]. It has good approximation ability to nonlinear problems. Therefore, the Kriging agent model was used to construct the response surface, with the five design variables of the hinge beam model as inputs, and the stress peak (P9), displacement peak (P10), volume (P11) and hinge beam mass (P12) as outputs, to establish the relationship between inputs and outputs. 100 groups of design points were selected for the training of the agent model, and 30 groups of design points were used to verify the accuracy of the response surface.

	A	B	C	D	E
1		P9 - Equivalent Stress Maximum	P10 - Total Deformation Maximum	P11 - Geometry Volume	P12 - Geometry Mass
2	Coefficient of Determination (Best Value = 1)				
3	Learning Points	1	1	1	1
4	Root Mean Square Error (Best Value = 0)				
5	Learning Points	2.4515E-06	1.3435E-07	0.45788	3.5943E-09
6	Verification Points	2.1558E-06	1.4351E-07	0.22039	1.73E-09
7	Relative Maximum Absolute Error (Best Value = 0%)				
8	Learning Points	0	0	0	0
9	Verification Points	0	0	0	0
10	Relative Average Absolute Error (Best Value = 0%)				
11	Learning Points	0	0	0	0
12	Verification Points	0	0	0	0

Figure 5. Precision evaluation of agent model.

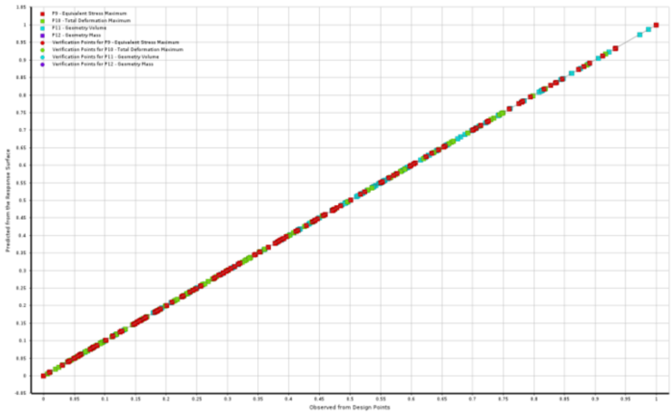


Figure 6. Distribution of sample points and verification points.

Figure 5 shows the goodness of fit of the agent model. As can be seen from the table, the root mean square error of Kriging agent model fitting, the relative maximum absolute error and the relative mean absolute error are both within the allowed error range, and the fitting accuracy of the agent model is generally good. As shown in Figure 6., is the coordinate distribution diagram of output predicted value and calculated value of sample points and verification points. The predicted value and calculated value are equal on the contour line, indicating that the fitting error is 0. As can be seen from the figure, their output points are basically scattered near the contour lines, which indicates that the fitting accuracy of the response surface meets the requirements and verifies the feasibility of the established agent model. It can be used for lightweight design.

5.3. optimization

On the basis of establishing the mathematical model of optimal design, the multi-objective genetic algorithm (MOGA) was combined to conduct optimization calculation[14~16]. Table 2 shows the candidate points finally obtained by the agent model combined with the optimization algorithm. As can be seen from the table, the error between the calculated value and the predicted value of the two candidate points is less than 2.1%, which verifies the fitting accuracy of the agent model. After comprehensive analysis of the structure and analysis results of the hinge beam, candidate point 1 is selected as the optimal scheme.

Table 2. Calculated and predicted values of the two candidate points after optimization.

Design point	X1	X2	X3	X4	X5	P9(MPa)	P10(mm)	P11(m m^3)	P12(KG)
Sample points 1	80.388	52.6	612.02	385.19	322.5	473.75	0.69234	4.2448E+8	3332.1
Predictive value 1						483.67	0.69412	4.2446E+8	3332
Sample points 2	80.388	52.6	611.47	385.33	322.5	473.39	0.69124	4.2463E+8	3333.4
Predictive value 2						482.97	0.69312	4.2462E+8	3333.3

The results before and after optimization are shown in Table 3. The strength and stiffness of the optimized hinged beam structure meet the requirements. The optimal results are mass 3332.1Kg, stress peak 473.75MPa (satisfying the allowable stress), and maximum displacement 0.69234mm. The original mass was 3684.2kg. Compared with the initial scheme, the mass and volume of the hinged beam are reduced by 9.55%, the maximum stress is increased by 3.52%, and the maximum displacement is increased by 3.24%, but they are all within the allowable range of the material. The weight of the optimized hinge structure is significantly reduced, and the purpose of lightweight is effectively realized.

Table 3. Comparison of results before and after optimization.

Design point	X1	X2	X3	X4	X5	P9(MPa)	P10(mm)	P11(m m^3)	P12(KG)
Before optimization	100	60	650	360	380	457.62	0.67059	4.6932E+8	3684.2
The optimized	80.388	52.6	612.02	385.19	322.5	473.75	0.69234	4.2448E+8	3332.1
decrease	-19.61%	-12.34%	-5.84%	6.99%	-15.13%	3.52%	3.24%	-9.55%	-9.55%

6. Conclusion

(1) SolidWorks parametric modeling combined with ANSYS Workbench finite element analysis provides a large number of sample points for agent model fitting, saving a lot of time and calculation cost.

(2) The hinged beam structure was analyzed by finite element method, and the stress peak value and displacement peak value in the analysis results were used as constraint conditions to check the strength and stiffness of the optimized design scheme, which ensures the accuracy and reliability of the hinge beam structure design.

(3) Kriging was used to build the agent model to fit the relationship between input and output, and multi-objective genetic algorithm was used to complete the lightweight design of hinged beam structure. Compared with the initial scheme, the mass of the final optimization scheme is reduced by 9.55%. Under the condition of satisfying the strength and stiffness, the quality of the hinge beam structure is improved obviously, which also provides a reference for the lightweight design of other mechanical parts.

Acknowledgments

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