MODAL ANALYSIS AND OPTIMIZATION OF MACHINE TOOL OBLIQUE COLUMN BASED ON ANSYS WORKBENCH

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In view of the experience dependence and inefficiency of traditional machine tool design and combined with Ansys Workbench's powerful finite element analysis ability, a multi-objective optimization method combining response surface and genetic algorithm is proposed. Taking the oblique column of a special machine tool as the research object, five dimension parameters were set as design variables, the experimental design points were obtained by Central Composite Design, and the Pareto optimal solution set was obtained by iterating the response surface model with MOGA algorithm, and select the candidate points that meet the requirements. The experimental results show that the quality of oblique column is reduced by 12.07% and the first natural frequency is increased by 26.8%. The optimization results meet the design requirements.

Keywords: The oblique column; Response surface; Genetic algorithm; Multi-Objective optimization

1. Introduction

With the continuous development of modern design theory and computer technology, the mechanical manufacturing industry has put forward higher requirements for machine tool accuracy, efficiency, reliability and so on. Traditional design relies on experience and analogy method has a long design cycle, which cannot respond to market demand in time. Digital design of machine tools by finite element method has become a hot research topic in many enterprises and universities at home and abroad. The literature [1] put forward the application of computer to the overall dynamic design and modeling of machine tools; Ya-hui WANG et al. [2] carried out static and dynamic analysis on the rolling mill with the help of computer, the mill structure was optimized and improved to reduce the production cost. The literature [3] studies the influence of symmetric and asymmetric structure on machine tool productivity by establishing simplified machine tool model; Sun-min Kim et al. [4] studied the influence of the combination mode between grinding spindle and grinding wheel on spindle

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performance by using finite element method. Using computer to carry out finite element simulation analysis can reduce research and development costs and improve product reliability.

The response surface method is to construct an explicit approximate expression to replace the implicit constraint or objective function in the original design problem, which shows great advantages in terms of global convergence and optimization efficiency [5]. At present, many scholars seek optimal solution by constructing a response surface model. Sahu N K et al.[6] analyzed the relationship between cutting force and surface roughness by response surface method. Asit Kumar Parida et al. [7] used the response surface method to carry out mathematical modeling of tooth surface wear and surface roughness, and the fitting results were in good agreement with the experimental results. All of the above studies have achieved good results.

The column is the core component of machine tool, which bears the movement of spindle and cutter. Its tiny vibration or deformation will directly affect the accuracy of parts processed. Therefore, it is necessary to carry out dynamic analysis of the column to improve its natural frequency and prevent resonance. In this paper, Solidworks software is used to model the oblique column of machine tool, and then it is imported into Ansys Workbench platform for dynamic modal analysis. Five parameters of column length, width, height, wall thickness and rib thickness are taken as design variables. Mass and first-order natural frequency is taken as optimization output variables, and the multi-objective genetic algorithm is used to improve the natural frequency and reducing the quality of oblique column. Fig. 1 is a column model of machine tool.
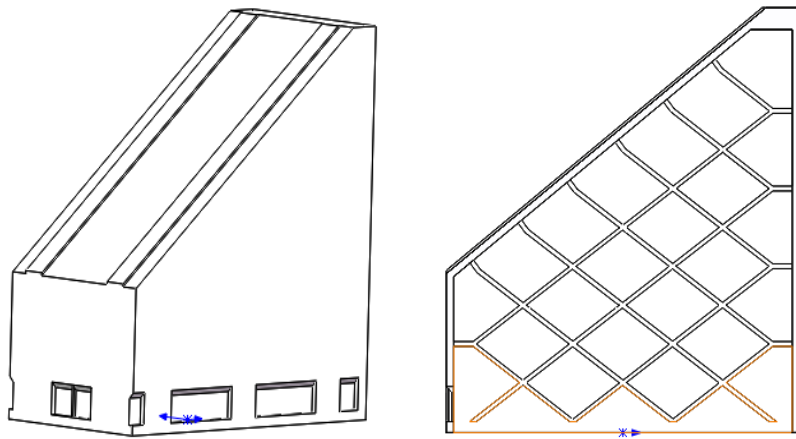

Fig.1.The Oblique Column Model

2. Finite Element Analysis of the Oblique Column

2.1 The Theoretical Basis of Modal Analysis

The finite element analysis needs to discretize the system first, and then the dynamic equilibrium equation of each node is as follows:

$$\{F_i\} + \{F_d\} + \{P(t)\} = \{F_e\} \tag{1}$$

$$\{F_e\} = [K]x(t) \tag{2}$$

According to the Darumbell Principle:

$$\{F_i\} = -[M]\ddot{x}(t) \tag{3}$$

If the system has viscous damping:

$$\{F_d\} = -[C]\ddot{x}(t) \tag{4}$$

Ultimately, the equation of motion can be obtained:

$$[M]\ddot{x}(t) + [C]\dot{x}(t) + [K]x(t) = P(t) \tag{5}$$

Make P(t)=0 available :

$$[M]\ddot{x}(t) + [C]\dot{x}(t) + [K]x(t) = 0 \tag{6}$$

Among them $\{F_i\}$ is the inertial force, $\{F_d\}$ is the damping force, $\{P(t)\}$ is the dynamic load, $\{F_e\}$ is the elastic force, $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $[C]$ is the damping matrix, $x(t)$ is the displacement.

The literature [8] introduces that machine tool structural damping mainly occurs in fixed or movable joint parts, and the internal damping of part materials is only a small part of the total energy absorbed and lost, so the machine tool parts can be regarded as undamped system approximately. Thus, the motion equation of undamped free vibration can be written:

$$[M]\ddot{x}(t) + [K]x(t) = 0 \tag{7}$$

Let the structure do simple harmonic motion $x(t) = \{\phi\}\cos\omega t$ .Bring in the formulas above：

$$[K]\{\phi\} = \omega^2[M]\{\phi\} \tag{8}$$

The amplitude is not all zero in free vibration:

$$\left|[K] - \omega^2[M]\right| = 0 \tag{9}$$

The natural frequency of order i can be obtained by mathematical calculation:

$$f_{pi} = \frac{1}{2\pi}\sqrt{\frac{k_i}{m_i}} \tag{10}$$

2. 2 The Model Import and the Mesh Generation

In order to ensure that the model established by Solidworks and the Workbench do not lose the bidirectional parameterized link of data; this experiment will directly open the Ansys Workbench from Solidworks. Details in the model, such as bolt holes, chamfering and small diameter holes, have little influence on the calculation results, but will increase a lot of computing time of the computer [9]. In order to improve the efficiency, the original model was simplified before the model was imported. In Workbench Engineering Data, the material selected is gray cast iron with Density $\rho = 7.2103\, kg/m^3$, Young's Modulus $E = 110$ GPa, Poisson's ratio $\upsilon = 0.28$.

Mesh generation is an important step in finite element analysis. Mesh size directly determines the accuracy of the calculation. In order to ensure a higher accuracy of the results, the size of the mesh should be smaller, but at the same time, the computing time of the computer will be greatly increased. In order to balance the quality of the mesh and the computing time, a tentative mesh generation is first carried out. The experimental results are shown in the Table.1.

Table.1

Grid Size, Grid Quality and Natural Frequency

Mesh Size(mm)		Free Division	20	25	30	35
Grid Quality		0.522	0.750	0.745	0.731	0.699
Natural Frequency (*Hz*)	First-order	101.020	98.446	98.722	98.903	99.279
	Second-order	107.690	104.210	104.570	104.770	105.160
	Third-order	158.210	154.160	154.570	154.780	155.070
	Fourth-order	158.780	154.680	155.070	155.290	155.780
	Fifth-order	174.600	167.420	168.100	168.470	169.250
	Sixth-order	206.010	200.150	200.990	201.420	201.890

It can be seen from the table that the natural frequency of the first-order changes little, but the mesh quality changes greatly. After comprehensive analysis, the mesh size is selected as 30mm. The grid correlation was set to 100, and the grid type was selected as a regular tetrahedral unit. Finally, a total of 82,439 nodes and 42,523 units were generated. The grid division effect is shown in the Fig. 2.
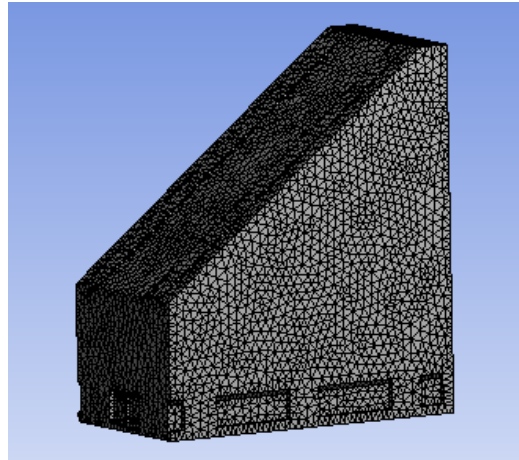
Fig.2. Effect Diagram of Mesh Generation

2.3 The Vibration Modes of the Column and Analysis of Result

Because the bottom of the oblique column is connected with machine tool by bolts in practical work, in order to simulate the real working condition of the column, fixed constraints should be imposed on the bottom of the oblique column, and the first six natural frequencies should be selected and calculated in the analysis settings. The results of calculation are generated into images; the modal diagram shown below is obtained.
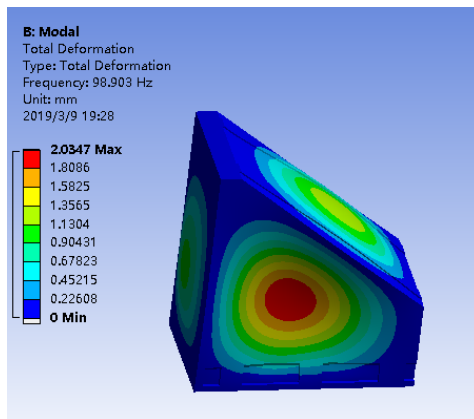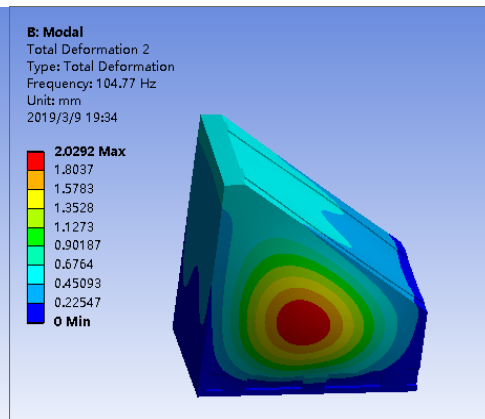

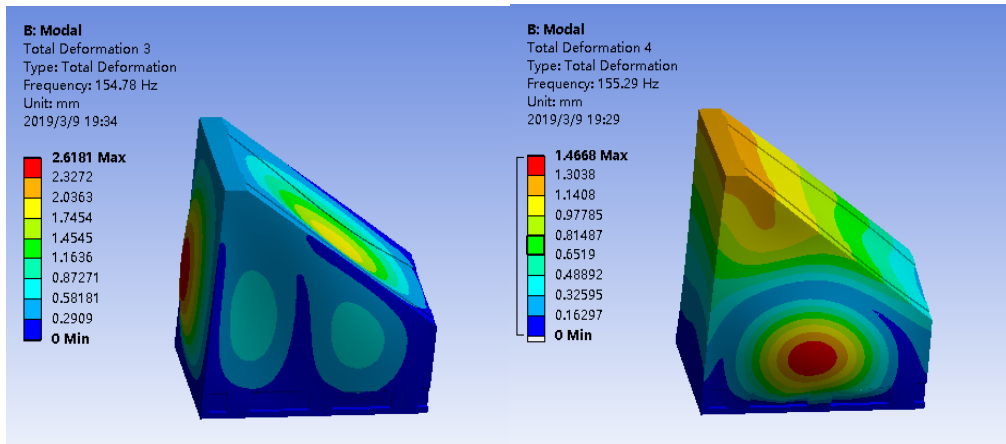Fig.3. First-order mode   Fig.4.Second-order mode

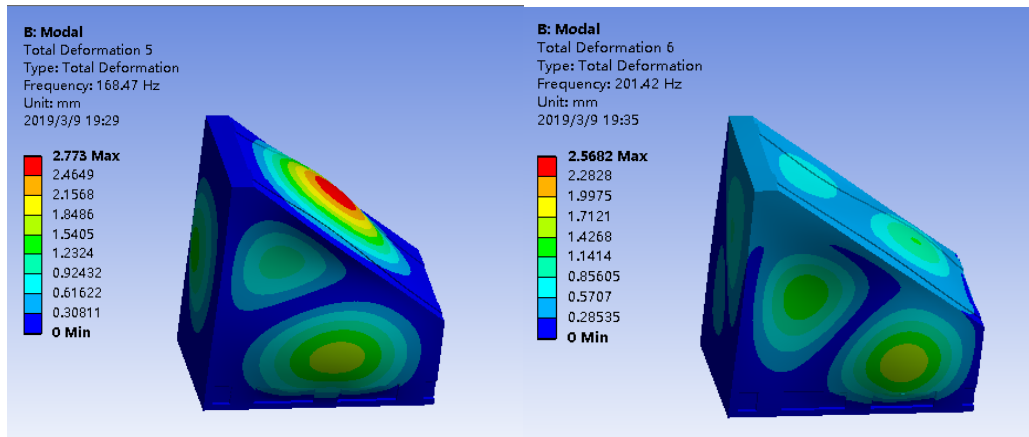Fig.5.Third-order mode   Fig.6. Fourth-order mode

Fig.7.Fifth-order mode   Fig.8. Sixth-order mode

Because the spindle speed of the machine tool is 1500 rev/min and the number of milling cutter teeth is generally 2 or 4, the machine tool will generate 100 Hz exciting force when it works. When the column frequency is lower than the exciting force, it is very likely to produce resonance, which will affect the processing accuracy of parts. It can be seen from Table.1 that the first natural frequency of the column must be increased.

2.4 The Design Method Selection and the Experimental Sample Point Generation

Response Surface Method (RSM) is a method of predicting the response value of non-test sample points by testing the generated experimental design points through the theory of experimental design. The response surface model is generated by these experimental design points, and the response surface model is

continuous. The more experimental design points are obtained, the closer the fitting model is to the real model, but too many design points will lead to a significant increase in calculation time. Selecting scientific experimental design methods to generate experimental design points can reduce a lot of calculation time at the expense of certain accuracy.

Central Composite Design is adopted in this experiment design. In the case of 2 levels and n factors, the experimental design point has one center, $2n$ axial points and $2^{n-\xi}$ factorial points constitute [10]. The calculation of experimental design points is shown in the Table.2. When the number of design variables is 5, ξ is 1, so this experiment will generate 1+10+16=27 experimental design points.

Table.2

The Number of Experimental Design Points

The Number of Design Variables	1	2	3	4	5	6	7	8	9	...
The Factorial coefficient ξ	0	0	0	0	1	1	1	2	2	...
The Number of Experimental Design Points	5	9	15	25	27	45	79	81	147	...

The value range of design variables can be customized and adjusted according to the actual situation. In this experiment, the value of each design variable is set according to the system default, namely 10% above or below. After calculation, the value range of each design variable is shown in the Table.3.

Table.3

The Range of Design Variables

	Rib thickness P1	Wall thickness P2	Width P3	Height P4	Length P5
Size Initial Value	20	33	850	1750	1550
Variable Scope	18-22	29.7-36.3	765-935	1575-1925	1395-1705

The experimental design points are solved in Workbench, and the updated results are shown in Table.4. P6 is the mass of the oblique column in kilograms; P7 is the first natural frequency of the oblique column in hertz.

Table.4

Generation and Solution of Experimental Design Points

Name	P1	P2	P3	P4	P5	P6	P7
1	20	33	850	1750	1550	1767.886	98.90278
2	18	33	850	1750	1550	1762.229	98.23578
3	22	33	850	1750	1550	1773.544	99.66362
4	20	29.7	850	1750	1550	1639.26	91.40975
5	20	36.3	850	1750	1550	1895.839	106.4833
6	20	33	765	1750	1550	1679.762	101.6236
7	20	33	935	1750	1550	1856.837	95.81809
8	20	33	850	1575	1550	1643.116	106.2717
9	20	33	850	1925	1550	1894.91	93.19413
10	20	33	850	1750	1395	1652.489	107.4062

11	20	33	850	1750	1705	1884.142	92.28092
12	19.43332	32.06498	825.9161	1700.416	1593.918	1702.639	97.18194
13	20.56668	32.06498	825.9161	1700.416	1506.082	1642.746	101.8087
14	19.43332	33.93502	825.9161	1700.416	1506.082	1708.671	105.8903
15	20.56668	33.93502	825.9161	1700.416	1593.918	1777.564	101.8636
16	19.43332	32.06498	874.0839	1700.416	1506.082	1687.629	99.68602
17	20.56668	32.06498	874.0839	1700.416	1593.918	1754.591	96.06298
18	19.43332	33.93502	874.0839	1700.416	1593.918	1824.588	99.88825
19	20.56668	33.93502	874.0839	1700.416	1506.082	1761.191	104.5186
20	19.43332	32.06498	825.9161	1799.584	1506.082	1707.307	97.82772
21	20.56668	32.06498	825.9161	1799.584	1593.918	1775.341	93.93793
22	19.43332	33.93502	825.9161	1799.584	1593.918	1846.966	97.69657
23	20.56668	33.93502	825.9161	1799.584	1506.082	1782.628	102.6171
24	19.43332	32.06498	874.0839	1799.584	1593.918	1822.424	92.08075
25	20.56668	32.06498	874.0839	1799.584	1506.082	1760.176	96.61536
26	19.43332	33.93502	874.0839	1799.584	1506.082	1830.605	100.4751
27	20.56668	33.93502	874.0839	1799.584	1593.918	1902.225	96.53699

2.5 The construction of Response Surface

When the number of design variables is n, the quadratic polynomial response surface model is as follows:

$$\gamma(x) = \beta_0 + \sum_{i=1}^{n}\beta_i x_i + \sum_{i=1}^{n}\beta_{ii} x_i^2 + \sum_{i=2}^{n}\sum_{j=1}^{i-1}\beta_{ij} x_i x_j \tag{11}$$

In the formula, x_i is the design variable, n is the number of design variables, β is unknown but it can be obtained by mathematical method.

The response surface model is constructed by using the Standard Response Surface-Full 2nd Order Polynomials at the above experimental design points. The fitting effect is shown in the Fig. 9.
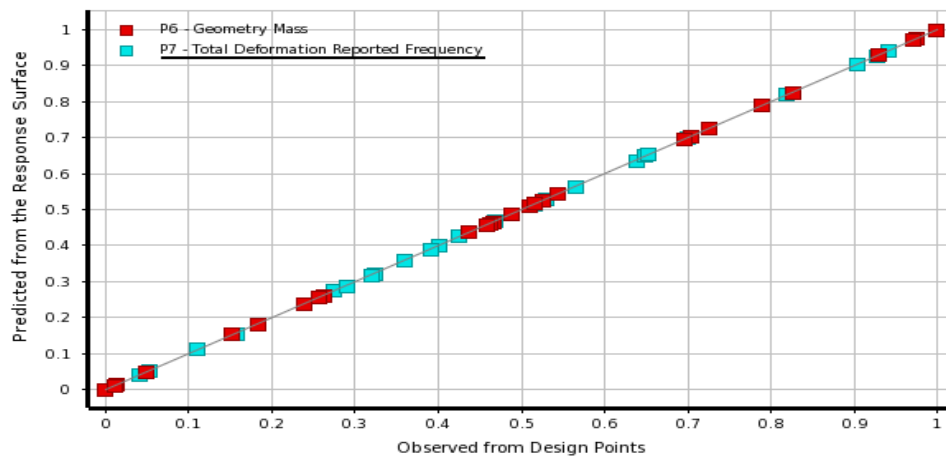

Fig.9.The Fitting Diagram of the Experimental Design Points

It can be seen from the fitting diagram that the experimental design points show a linear relationship, and the experimental fitting effect is good.
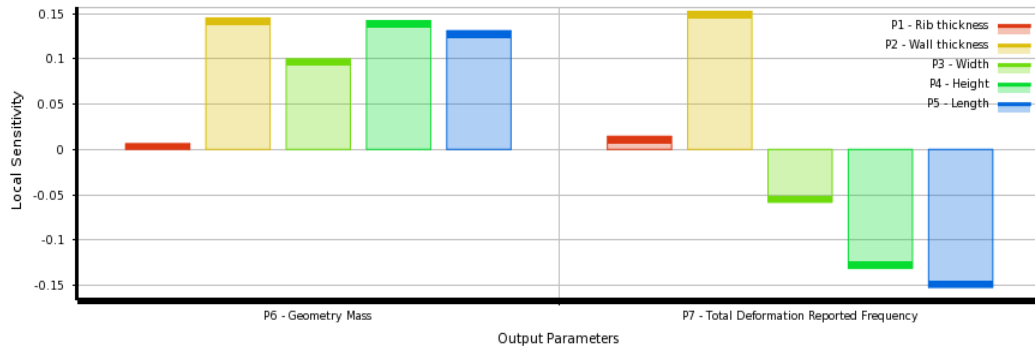

Fig.10. Local Sensitivity

From the local sensitivity figure10, it can be seen that the thickness of rib reinforcement P1 has little influence on the first-order natural frequency of column. Wall thickness P2, height P4 and length P5 have great influence on natural frequencies. The wall thickness is proportional to the natural frequency, while the length and height are inversely proportional to the natural frequency. The effect of height and length on natural frequency is basically the same. Therefore, in order to increase the first natural frequency, the wall thickness should be increased, while the height and length should be reduced.

Through the above analysis, the wall thickness and first-order natural frequency response surface, the height and first-order natural frequency response surface are obtained respectively as shown in figure11 and figure12.
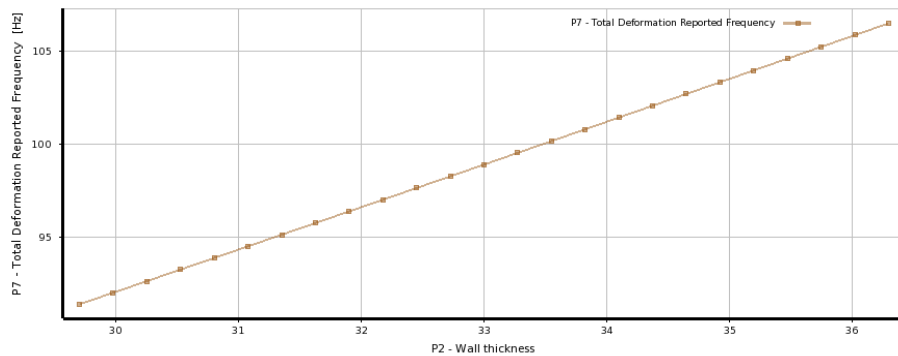

Fig.11.The Wall Thickness and First-order Natural Frequency Response Surface Diagram
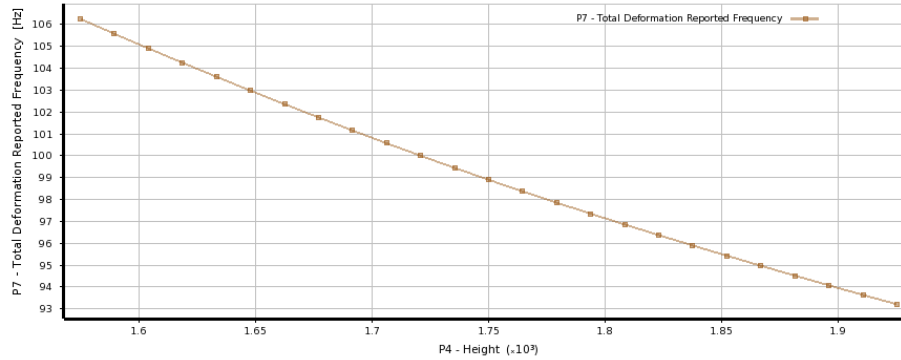
Fig. 12. The Height and First-order Natural Frequency Response Surface Diagram

2.6 The Optimization of Mathematical Model

Optimization design is to use some mathematical methods to select the desired results from a series of solutions by using optimization design theory. In this design, five parameters which determine the size of the column are selected as design variables. The optimization objective is to increase the first-order natural frequency of the oblique column, in order to meet the principle of lightweight design and minimize the mass of the oblique column. So the optimal design model is as follows:

$$\begin{cases} M(P) = \min M(P1, P2, P3, P4, P5) \\ f(P1,\ P2,\ P3,\ P4,\ P5) > 100Hz \\ \qquad 18 \le P1 \le 20 \\ \qquad 29.7 \le P2 \le 36.3 \\ \qquad 765 \le P3 \le 935 \\ \qquad 1575 \le P4 \le 1925 \\ \qquad 1395 \le P5 \le 1705 \end{cases} \qquad (12)$$

2.7 Introduction of Genetic Algorithm

Most optimization problems in the field of scientific research and engineering are multi-objective optimization problems [11]. There are many methods to solve constrained multi-objective optimization problems [12], among which genetic algorithm is widely used. Genetic algorithm (GA) is derived from the evolution of natural species, which refers to the simulation of inter-species genetic, mutation, hybridization and other factors. Multi-objective genetic algorithm (MOGA) solves multi-objective optimization problems by applying Pareto theory on the basis of genetic algorithm. At present, many scholars use genetic algorithm to solve multi-objective optimization problems and get good results. Wang Y H et al. [13] applied MOGA algorithm to optimize the

hydrodynamic performance of floating body based on the response surface constructed by neural network. S. Selvakumaret al. [14] found the optimum combination of tool wear and surface roughness by combining MOGA algorithm with sensitivity analysis. Mousavi-Avval S H et al. [15] used multi-objective genetic algorithm to study the optimal combination of mixed energy, economic index and environmental index in rapeseed production [16].

2.8 Optimization Results

Ansys Workbench provides four optimization methods. In this experiment, The Multi-Objective Genetic Algorithm (MOGA) is selected to set the initial population number to 100, the maximum allowable proportion of Pareto to 70%, and the maximum number of iterations to 20. In the target and constraint, the size parameters are no longer limited, the mass is set to the minimum, the first natural frequency is set to the maximum, and the Pareto solution is obtained as shown in figure13.
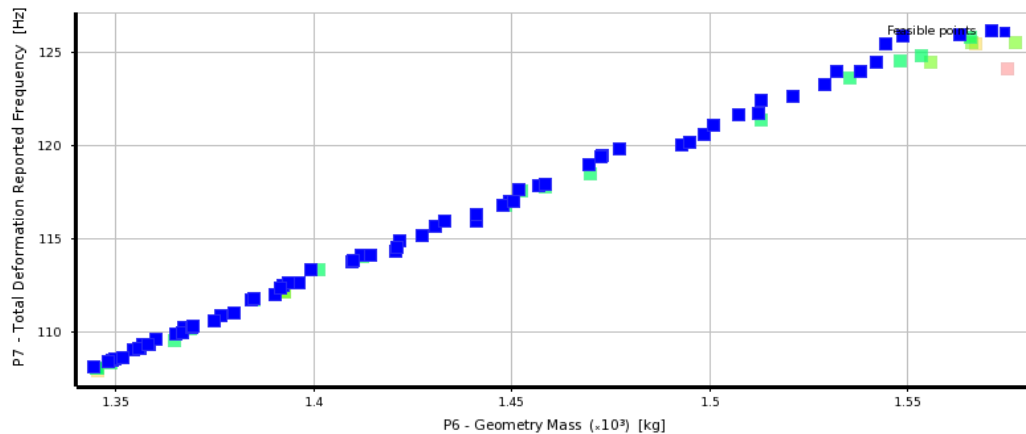

Fig.13.The Pareto Solution Set

Pareto solution is a series of effective solutions generated in the process of multi-objective optimization. There is no good or bad between the solutions. It is necessary to select the solution that meets the needs according to the actual situation and design requirements. From the figure13, it can be seen that there is a stable region after the Pareto solution set increases, and then there is a downward trend. Before the mass is 1571.3 kg, the natural frequency increases with the increase of mass, and then decreases with the increase of mass. Therefore, turning points can be selected as a set of optimization candidates if the first-order natural frequency is maximized. Table.5 shows three candidate point schemes given by the system.

Table.5

Optimizing Candidate Selection

Name	P1	P2	P3	P4	P5	P6 - Mass (kg)		P7 - Frequency (Hz)	
						Parameter Value	Variation from Reference	Parameter Value	Variation from Reference
Candidate Point 1	21.164	35.787	766.02	1578	1395.8	1548.9	-12.39%	125.97	27.36%
Candidate Point 2	21.231	35.977	768.58	1585.3	1396.4	1563.2	-11.58%	126.02	27.41%
Candidate Point 3	19.934	35.339	766.64	1576.9	1397.6	1532.2	-13.33%	124.06	25.43%
Candidate Point 3	19.934	35.339	766.64	1576.9	1397.6	1532.4	-13.32%	124.15	25.53%
Reference	20	33	850	1750	1550	1767.9	0.00%	98.904	0.00%

It can be seen from the three groups of optimization candidate points that the natural frequencies of the first-order all reach above $100\,Hz$ and all meet the design requirements. The optimization result of candidate point 3 has the lowest quality, resulting in a mass reduction of 13.32%. Therefore, candidate point 3 is selected as the optimal solution of the optimization design.

Considering the actual processing conditions, the dimension parameters are adjusted, and the results are shown in the Table.6.

Table.6

Data Optimization and Integration Comparison

	P1(mm)	P2(mm)	P3(mm)	P4(mm)	P5(mm)	Mass(mm)	First-order frequency(hz)
Optimization results	19.934	35.339	766.64	1576.9	1397.6	1532.2	124.06
Rounding results	20	36	767	1577	1398	1554.5	125.41

The calculated results show that the mass of the rectified oblique column decreases by 12.07% and the first-order natural frequency increases by 26.8%. The experimental results meet the design requirements.

3. Conclusions

In this paper, Ansys workbench platform is used for dynamic modal analysis of machine tool oblique column. It is found that the first-order natural frequency of the column is too low. Five-dimension parameters are taken as design variables. Test sample points were obtained through the Center Composite Design, and the response surface model was constructed by using the sample points, and the optimal size was obtained through the optimization solution of the

response surface model by genetic algorithm. Finally, the quality of the oblique column is reduced by 12.07%, and the first-order natural frequency is increased by 26.8%. The method used in this paper not only reduces the weight of equipment, but also improves the seismic performance. It can improve the structure of equipment, guide production and prevent resonance of equipment in the working process. The quality reduction satisfies the principle of lightweight design, reduces the production cost, and has higher economic benefits. It has a guiding role in product development and improvement and can be extended to a wider range of fields.

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