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

Yahui WANG¹, Shaoqun XING¹, Feifan LI¹, Jinmei WU¹, Tao ZHANG¹

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

¹School of Mechanical Engineering, North China University of Water Resources and Electrical Power Zhengzhou, Henan 450045, China
Email: wangyahui@ncwu.edu.cn
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](image-url)
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:

\[\{F_i\} + \{F_d\} + \{P(t)\} = \{F_e\}\]  \hspace{1cm} (1)

\[\{F_e\} = [K]x(t)\]  \hspace{1cm} (2)

According to the Darumbell Principle:

\[\{F_e\} = -[M]\ddot{x}(t)\]  \hspace{1cm} (3)

If the system has viscous damping:

\[\{F_d\} = -[C]\dddot{x}(t)\]  \hspace{1cm} (4)

Ultimately, the equation of motion can be obtained:

\[[M]\dddot{x}(t) + [C]\dddot{x}(t) + [K]x(t) = P(t)\]  \hspace{1cm} (5)

Make \(P(t) = 0\) available:

\[[M]\dddot{x}(t) + [C]\dddot{x}(t) + [K]x(t) = 0\]  \hspace{1cm} (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:

\[[M]\dddot{x}(t) + [K]x(t) = 0\]  \hspace{1cm} (7)

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

\[[K]\phi = \omega^2[M]\phi\]  \hspace{1cm} (8)

The amplitude is not all zero in free vibration:

\[[K] - \omega^2[M]\] = 0\]  \hspace{1cm} (9)

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

\[f_{pi} = \frac{1}{2\pi} \sqrt{\frac{k_i}{m_i}}\]  \hspace{1cm} (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 $\rho = 7.2103 \, \text{kg/m}^3$, Young’s Modulus $E = 110$ GPa, Poisson’s ratio $\nu = 0.28$.

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>
<thead>
<tr>
<th>Mesh Size (mm)</th>
<th>Free Division</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Quality</td>
<td>First-order</td>
<td>0.522</td>
<td>0.750</td>
<td>0.745</td>
<td>0.731</td>
</tr>
<tr>
<td></td>
<td>Second-order</td>
<td>107.690</td>
<td>104.210</td>
<td>104.570</td>
<td>104.770</td>
</tr>
<tr>
<td></td>
<td>Third-order</td>
<td>158.210</td>
<td>154.160</td>
<td>154.570</td>
<td>154.780</td>
</tr>
<tr>
<td></td>
<td>Fourth-order</td>
<td>158.780</td>
<td>154.680</td>
<td>155.070</td>
<td>155.290</td>
</tr>
<tr>
<td></td>
<td>Fifth-order</td>
<td>174.600</td>
<td>167.420</td>
<td>168.100</td>
<td>168.470</td>
</tr>
<tr>
<td></td>
<td>Sixth-order</td>
<td>206.010</td>
<td>200.150</td>
<td>200.990</td>
<td>201.420</td>
</tr>
</tbody>
</table>

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.
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.2. Effect Diagram of Mesh Generation

Fig.3. First-order mode

Fig.4. Second-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
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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 \( n-2 \) factorial points constitute [10]. The calculation of experimental design points is shown in the Table.2. When the number of design variables is 5, \( \xi \) is 1, so this experiment will generate \( 1+10+16=27 \) experimental design points.

Table 2

| The Number of Design Variables | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | ...
|-------------------------------|----|----|----|----|----|----|----|----|----|----|
| The Factorial coefficient \( \xi \) | 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

<table>
<thead>
<tr>
<th>The Range of Design Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rib thickness P1</td>
</tr>
<tr>
<td>Size Initial Value</td>
</tr>
<tr>
<td>Variable Scope</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Generation and Solution of Experimental Design Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<td>8</td>
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<tr>
<td>9</td>
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<tr>
<td>10</td>
</tr>
</tbody>
</table>
2.5 The construction of Response Surface

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

\[
\gamma(x) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_i x_i^2 + \sum_{i=2}^{n} \sum_{j=1}^{i-1} \beta_{ij} x_i x_j
\]

(11)

In the formula, \( x_i \) is the design variable, \( n \) is the number of design variables, \( \beta \) 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](image-url)
It can be seen from the fitting diagram that the experimental design points show a linear relationship, and the experimental fitting effect is good.

From the local sensitivity figure 10, 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 figure 11 and figure 12.
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:

\[
\begin{align*}
M(P) &= \text{min } M(P_1, P_2, P_3, P_4, P_5) \\
&\text{subject to: } f(P_1, P_2, P_3, P_4, P_5) > 100\text{Hz} \\
&\quad 18 \leq P_1 \leq 20 \\
&\quad 29.7 \leq P_2 \leq 36.3 \\
&\quad 765 \leq P_3 \leq 935 \\
&\quad 1575 \leq P_4 \leq 1925 \\
&\quad 1395 \leq P_5 \leq 1705
\end{align*}
\]

(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
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.

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.
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.

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.

**REFERENCES**


