RESPONSE SURFACE OPTIMIZATION OF MACHINE TOOL COLUMN BASED ON ANSYS WORKBENCH

Jin Xiangjie, Zhang Cai, Wang Chong
School of Machinery, North China University of Water Resources and Electric Power,
Zhengzhou, Henan, 450045, China.
Email: Jinxiangjie@ncwu.edu.cn

***ABSTRACT**: The column is the key part connecting the machine bed and the head stock. Its performance directly affects the accuracy of the machined parts. In this paper, after static and dynamic analysis of a machine tool column, it is found that the dynamic stiffness of the machine tool is low. Firstly, ANSYS Workbench was used to analyze the dimensional sensitivity of the column, and the parameters that had a great impact on the natural frequency were found out. Then, response surface optimization method was used to optimize the column. Obtain experimental design points through the Central Compound Design, use the Gene Aggregation method to fit the response surface, and finally use NSGA-II algorithm to perform mufti-objective optimization on the fitted response surface. While increasing the natural frequency of the column, it reduces its quality, improves the performance of the machine tool and reduces the production cost. The optimization results show that compared with the original design, the column quality is reduced by 7.3%, and the natural frequency is increased by 24.49%.*

***KEYWORDS**: Column; Natural frequency; Multi-objective optimization; Response surface; NSGA-II*

1 INTRODUCTION

The basic equipment manufacturing industry is the foundation of the national economy. CNC machine tools are used as parts processing mother machines. Their processing quality and production capacity determine the development level of the manufacturing industry. The development of numerical control industry, especially the research on the high precision, high speed and high stability of numerical control machine tools, plays an important role in the technological transformation, transformation and upgrading of machinery manufacturing industry, and is the top priority of the development of high-end technology industry. Nowadays, the manufacturing industry has higher and higher requirements for the precision of parts. Many countries also take the research and development of precision and ultra precision machine tools as key projects. (Bere, Berce and Nemes. 2012). In order to maintain high accuracy of high-speed machine tools under high acceleration, it is necessary to have small mass and high rigidity of moving parts of machine tools, and use the least structural materials to bear the maximum external force, that is to say, to achieve high specific rigidity, that is, the best structural efficiency (CEN H. T., 1992) carried out an experimental study on the dynamic performance of the whole machine for MS1320 high-speed cylindrical grinder to 2004). The column is one of the key parts connecting the machine bed and the main axle box. Its small vibration or deformation will directly affect the accuracy of the processed parts, so it needs to have enough rigidity and seismic resistance. At present, many experts and scholars at home and abroad have made in-depth research on the performance analysis and optimization of machine tools. (Li Xiuyi et al, 1992) carried out an experimental study on the dynamic performance of the whole machine for MS1320 high-speed cylindrical grinder to find out the weak links and main vibration sources of the machine. The machine is analyzed dynamically by means of experimental mode analysis, and the low order natural frequency and damping ratio of the machine are obtained. The forced vibration caused by the dynamic force of the drive parts of the grinding machine was diagnosed by the empty running test of the machine tool, and the internal vibration source of the grinding machine was found, and the improvement measures were put forward. (Ding, Zhang and Zhang, 2019) put forward a design method for the position of three-point support bed mat, and obtained the arrangement rule of three-point support bed. (Li Yupeng et al., 2019) Take a column as the research object, take the minimum strain energy and the maximum natural frequency of the first order as the objectives, take the volume fraction as the constraint, carry out the topology optimization of the heavy column structure, and get the optimal distribution of materials under the complex load. (Wu J. et al. 2009) studied the stiffness problem of a five degree of freedom hybrid machine tool with drive redundancy, simplified the structure of the machine tool into a combination of several units, deduced the stiffness matrix of each component of the machine tool, established the accurate stiffness model of the machine tool using the assembly method and improved the machine tool parts with the lowest stiffness. (Myerset al. 2003)a used the finite element method to analyze the static and dynamic stiffness characteristics of vertical milling machine. It is found that the vibration level is relatively low in the finishing process and the lack of dynamic stiffness results in poor surface finish of the machined parts. (Kolar P et al. 2010) studied the influence of machine frame on the dynamic characteristics of tool end through experiments and coupling simulation model. All the above researches have achieved good results, which greatly promoted the development of high-precision machine tools.

At present, there are three main methods to solve structural optimization problems. First, optimize according to the rich experience of designers. The other is to test different schemes and find out the best result through comparison. The third is to establish mathematical model and solve it to obtain the optimal strategy. Due to the continuous development of mathematical methods and high-performance computers, the technology of using mathematical modeling and numerical simulation to deal with structural optimization problems has gradually become the mainstream research method (Yanget al. 2017). The common optimization methods are direct optimization method and response surface optimization method. The direct optimization method obtains several experimental design points through the experimental design method, and then solves the experimental design points one by one to find the optimal solution, so the calculation is large and the solution efficiency is low. Response surface optimization is to construct explicit approximate expressions to replace implicit constraints or objective functions in the original design problem (Kurtaran & Erzurumlu, 2005), which greatly improve the efficiency of optimization. In this paper, the static and dynamic analysis of the machine tool column is carried out to see whether its static and dynamic stiffness meet the design requirements, and the weak links of the column are optimized to improve the specific stiffness. In the finite element simulation analysis of the column, remove the details that have little impact on the results but will increase a lot of calculation time, and use Solid Works to establish the three-dimensional model of the column as shown in Figure 1.

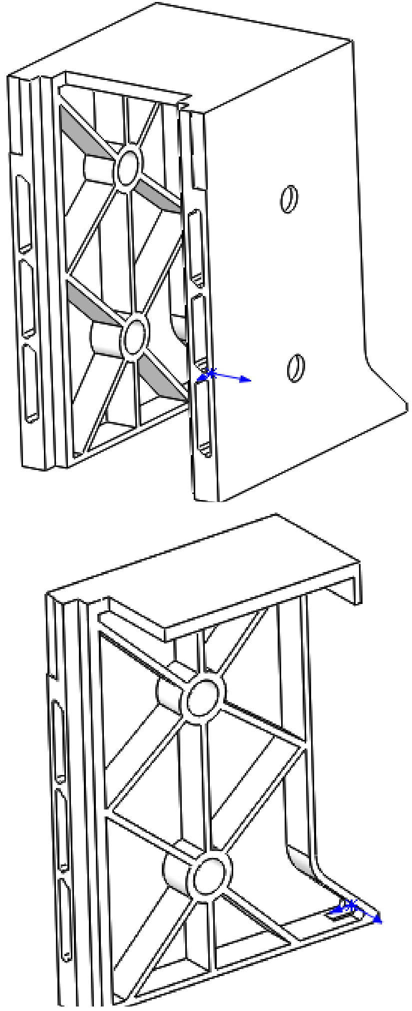

Fig. 1 3D model of column

2 STATIC ANALYSIS OF COLUMN

Linear static analysis means that the system returns to its original state after unloading, and there is no residual deformation and residual stress (Yu et al. 2012). Static analysis is to solve the response of the structure under static load, which focuses on the stress and deformation of the structure. The general dynamic analysis equation of the structure is as follows.

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F(t)\} \qquad (1)$$

Where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $F(t)$ is the combined external force, and $\{x\}$ is the displacement matrix.

Without considering the influence of inertia force and damping force, the term with time participation is removed to get formula (2).

$$[K]\{x\}=\{F(t)\} \qquad (2)$$

The column of the machine tool is made of cast iron, and its basic property parameters are shown in

Table 1.

Table 1: Column material properties

Material	**Density (kg/m^3)**	**Poisson's ratio**	**Modulus of elasticity (Gpa)**
cast iron	7200	0.28	110

After several attempts, considering both grid quality and computing time, the grid size was set to 20mm. The grid cell quality assessment was shown in table 2. After partition, the number of grid cells is 34693 and the number of nodes is 67490.

Table 2 Quality assessment of grid cells

Element Quality	**Jacobian Ratio**	**Aspect Ratio**	**Warping Factor**	**Warping Factor**	**Parallel Deviation**
0.702	1.074	2.333	0	0	0

The fixed constraint is applied at the bottom of the column, and the force of 3000n is applied on the sliding surface. The results of maximum deformation and maximum stress are shown in Fig. 2 and Fig. 3 below.

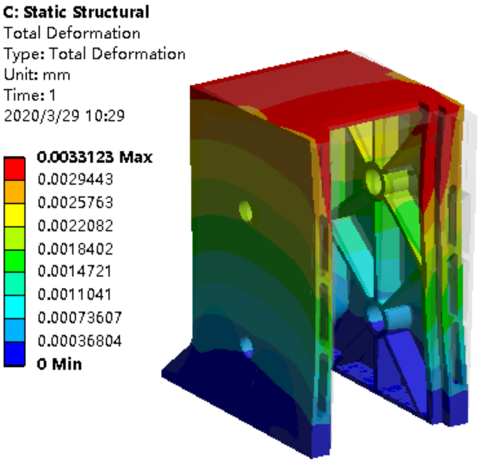

Fig. 2 deformation cloud image

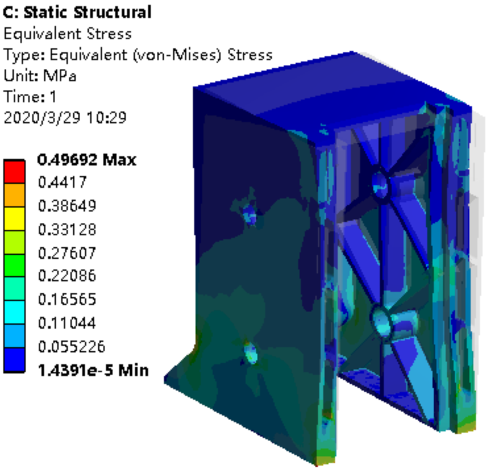

Fig. 3 stress cloud diagram

According to the deformation cloud map and stress cloud map, the maximum deformation of the column is 0.0033mm and the maximum stress is 0.31mpa, which is lower than the allowable stress of the material. Therefore, the statics characteristics fully meet the design requirements, and the design has a large space for optimization.

3 COLUMN MODAL ANALYSIS

According to reference (Konishberg, et al. 1992), the machine parts can be regarded as undimmed system approximately, and formula 1 can be changed into:

$$[M]\{\ddot{x}\}+[K]\{x\}=0 \tag{3}$$

Set up structure to do simple harmonic motion $\{x\}=\{\phi\}\sin(\omega t+\psi)$, because free vibration amplitude is not completely zero:

$$\left|[K]-\omega^2[M]\right|=0 \tag{4}$$

Finally, it can be concluded that the ithnatural frequency is:

$$f_{pi}=\frac{1}{2\pi}\sqrt{\frac{k_i}{m_i}} \tag{5}$$

In the modal analysis of the column, only the fixed constraint is applied at the bottom, and the first four modes of the column are shown in Figures 4-7.

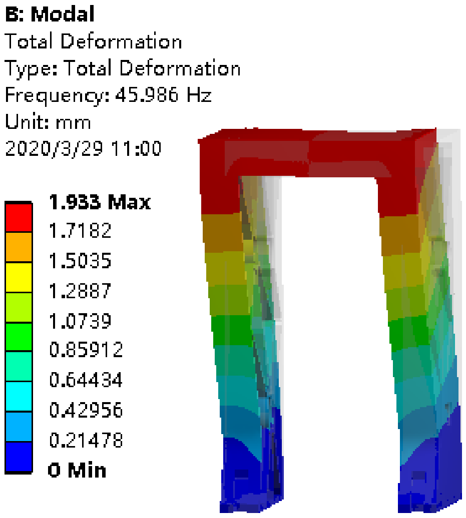

Fig. 4 first order mode

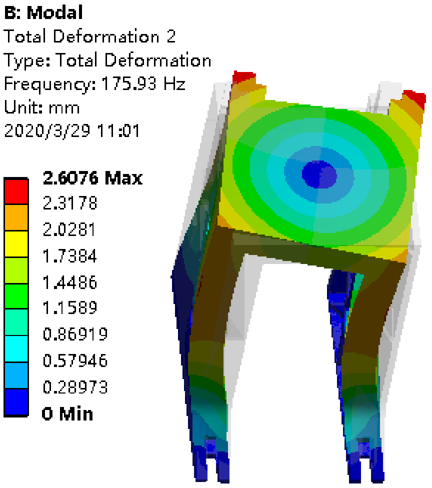

Fig. 5 second order mode

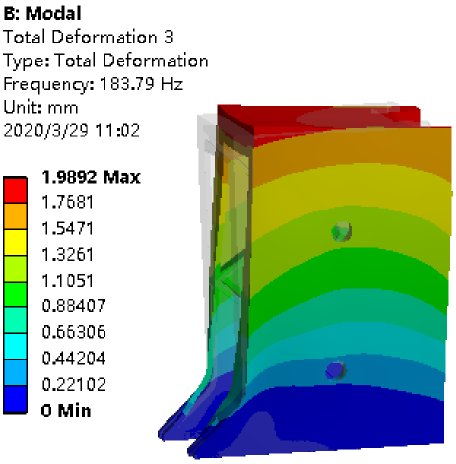

Fig 6 third order mode

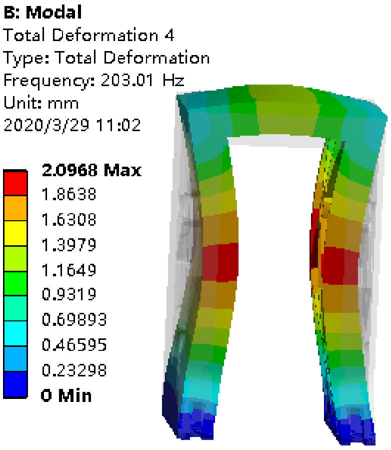

Fig. 7 fourth order mode

Table 3: First six modes and natural frequency of column

Order	natural frequency (Hz)	Vibration mode
1	45.986	Shimmy along the Y-axis
2	175.93	Torsion centered on the z axis
3	183.79	Shimmy along the X-axis
4	203.01	The lateral walls of the column shimmy inwards

When the machine tool is running at a normal speed of 1500r/min, it will generate an excitation force of about 50 Hz when it is working. The first order natural frequency is too low, which is easy to cause the generation of resonance with the excitation force, and the dynamic stiffness of the machine tool is insufficient. Therefore, it is necessary to optimize the dynamic performance of the column and improve the first order natural frequency.

4 OPTIMUM DESIGN OF COLUMN STRUCTURE

According to the previous analysis, the first-order natural frequency of the column is low, so the goal of this optimization is to improve the first-order natural frequency under the condition of the lowest quality. Due to the large number of column size parameters, if all of them are taken as design variables, not only the optimization effect will be reduced, but also the calculation time will be greatly increased. Therefore, it is necessary to select the parameters that have a greater impact on the optimization objectives from many sizes.

4.1 Parameter correlation analysis

The purpose of this parameter correlation analysis is to find out the size parameters that have a greater impact on the quality and natural frequency. Firstly, the column length (P1), width (P2), height (P3), lateral wall thickness (P4), upper wall thickness (P5), rib width (P6) and rib thickness (P7) are selected as input parameters for correlation analysis. Using the parameter correlation analysis function provided by ANSYS Workbench, Spearman was selected as the correlation analysis type, and the correlation relationship table was shown in table 4.

From the correlation table, we can see the correlation degree of each parameter to the objective function. The value 1 represents positive correlation and - 1 represents negative correlation. In this design, the size parameter greater than 0.5 is selected as the optimal design variable.

Table 4: Parameter correlation

The variable name	correlation	
	Mass	Natural frequency
P1	0.191	-0.163
P2	0.013	-0.203
P3	0.250	-0.620
P4	0.790	0.374
P5	0.035	-0.067
P6	0.330	0.163
P7	0.345	0.624

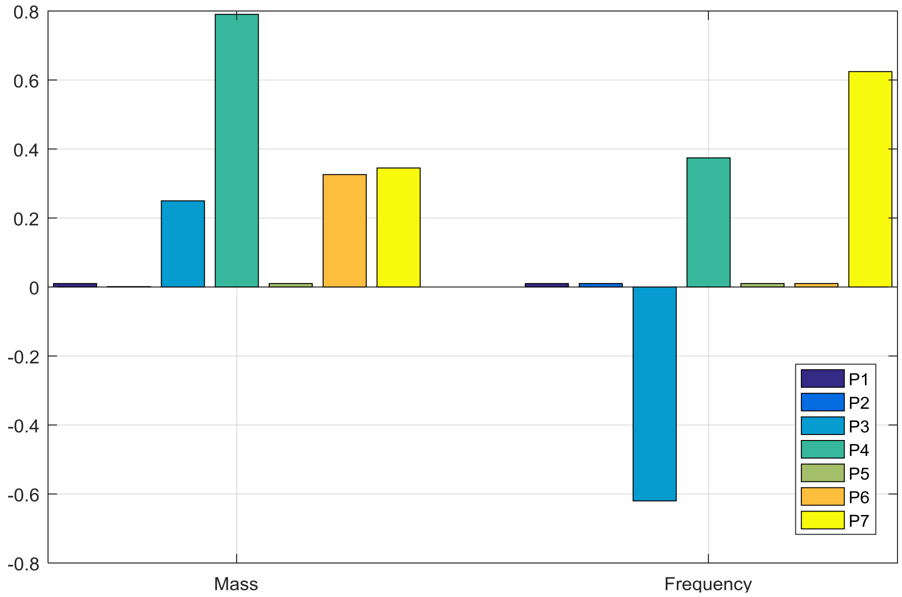

Fig. 8 Parameter sensitivity diagram

Fig. 8 is the sensitivity diagram of size parameters, from which we can intuitively see the influence degree of each size change on the target. Based on the comprehensive analysis of table 4 and figure 8, the column height (P3), lateral wall thickness (P4), rib width (P6) and rib thickness (P7) were finally selected as the design variables of this optimization design. The variation ranges of each design variable are shown in table 5.

Table 5: value range of design variables (Unit: mm)

Variable	**Height(P3)**	**lateral wall thickness(P4)**	**rib width (P6)**	**rib thickness (P7)**
Initial value	20	35	30	920
Upper limit	30	40	35	803
Lower limit	18	30	25	657

4.2 Generation of experimental design points

There are many methods to generate experimental design points, such as orthogonal experiment method, Latin hyper vertical method, etc. The central composite design method is adopted in this design, which is more suitable for experiments with factor number in the range of 2-6, and the number of tests is generally 14-90. There are four design variables in this design, and 25 sets of experimental design points are generated by the central composite method, some of which are shown in table 6.

Table 6: Experimental design points

Order	**P3**	**P4**	**P6**	**P7**	**Mass**	**Frequency**
1	1200	22.5	22.5	105	731.5407	47.70543
2	1100	22.5	22.5	105	686.906	54.9834
3	1300	22.5	22.5	105	777.4308	41.81146
4	1200	15	22.5	105	612.1119	44.21636
5	1200	30	22.5	105	850.7015	51.24984
6	1200	22.5	15	105	691.1397	45.80239
7	1200	22.5	30	105	772.4245	49.24406

8	1200	22.5	22.5	90	676.7142	41.89122
9	1200	22.5	22.5	120	786.3672	53.44747
…	…	…	…	…	…	…
23	1270.421	17.21846	27.78154	115.5631	747.0533	45.9352
24	1129.579	27.78154	27.78154	115.5631	847.941	61.26133
25	1270.421	27.78154	27.78154	115.5631	926.9345	50.41556

4.3 Response surface construction

Response surface construction is to use mathematical methods to fit experimental design points. ANSYS Workbench provides a variety of response surface construction methods, such as Standard second-order response surface, Kriging response surface, Non-parametric regression response surface, and so on. In this design, response surface model is generated by Gene Aggregation. In this method, genetic algorithm is used to solve the different types of response surface generated in parallel, taking into account the accuracy and stability of the response surface at the design point, so the genetic aggregation model is more reliable than the classical response surface model. The mathematical model of Gene Aggregation is as follows:

$$\hat{y}_{ens}(x) = \sum_{i=1}^{N_M} w_i \cdot \hat{y}_i(x)$$

Where $\hat{y}_{ens}$ is the prediction of the ensemble, $\hat{y}_i$ is the prediction of the i-th response surface, N_M is the number of met models used and $N_M \geq 1$, w_i is the weight factor of the i-th response surface. The weight factors satisfy: $\sum_{i=1}^{N_M} w_i = 1$ and $w_i \geq 0$, $1 \leq i \leq N_M$

Since many response surfaces can be formed between different size variables and different output parameters, we will not enumerate them here. The response surface model constructed by column height, rib thickness and column quality is shown in Fig. 9. The response surface model constructed by column height, rib thickness and first-order natural frequency is shown in Fig. 10.

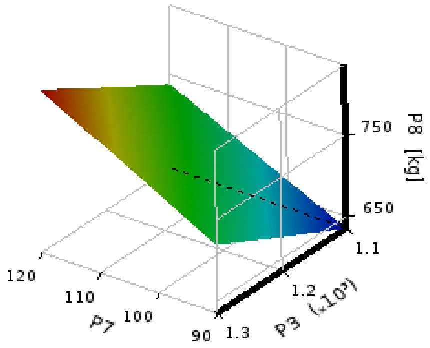

Fig.9 Mass response surface

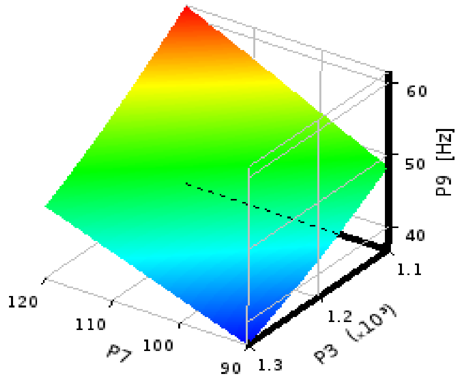

Fig. 10 Natural frequency response surface

Fig. 11 shows the fitting degree of mass and natural frequency. It can be seen from the figure that the response has a good fitting degree to the experimental design points, and the experimental design points are basically all on the response surface model.

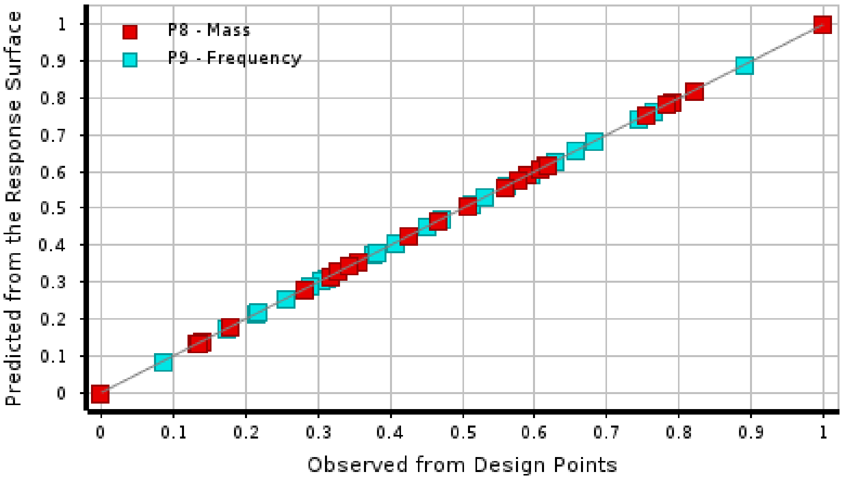

Fig. 11 Fitting degree diagram of experimental design points

4.4 Response surface optimization

The goal of this optimization is to maximize the natural frequency with as little mass as possible. There are two optimization objectives, so the design belongs to the multi-objective optimization problem, multi-objective optimization cannot find the absolute optimal solution, but through the optimization algorithm can find a series of relatively optimal solution sets, namely Pareto solution sets. Genetic algorithm has strong global optimization ability, and is an effective method to solve the multi-objective optimization problem of target conflict (Ununeet et al. 2018; Selvakumar & Ravikumar, 2018). Therefore, this design adopts genetic algorithm for optimization.

NSGA-II is one of the most widely used genetic algorithms. This method introduces the crowding ranking criterion, and stratified the population individuals according to the dominant relationship between individuals before the selection operator is executed (Rajesh & An and, 2012; Selvakumar & Ravikumar, 2018). At the same time, the elite strategy is used to enable the father to find the excellent individual to inherit to the next generation, so as to ensure that the excellent individual is not discarded in the evolution. It is convenient to find out the quality of individuals in the same stratified population through the crowding degree ranking criterion. The flow chart of NSGA-II algorithm is shown in Figure 12.

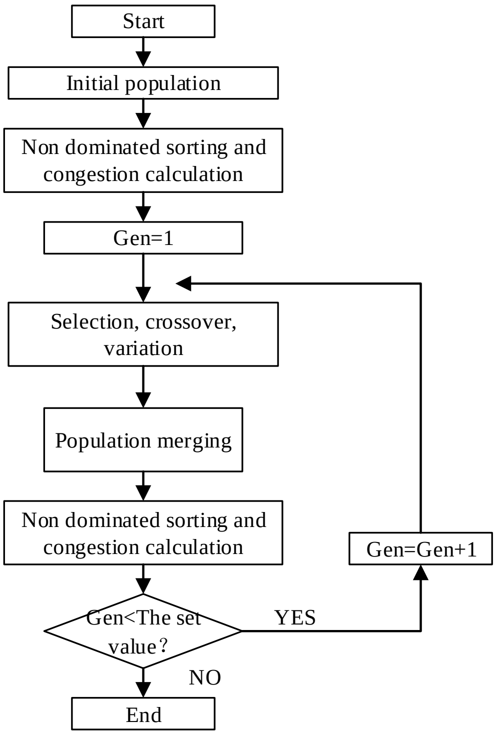

Fig. 12 NSGA-II algorithm flow chart

In this optimization design, the initial population number is set as 100 and the maximum number of iterations is 200. The Pareto solution set obtained by the final optimization is shown in figure 13.

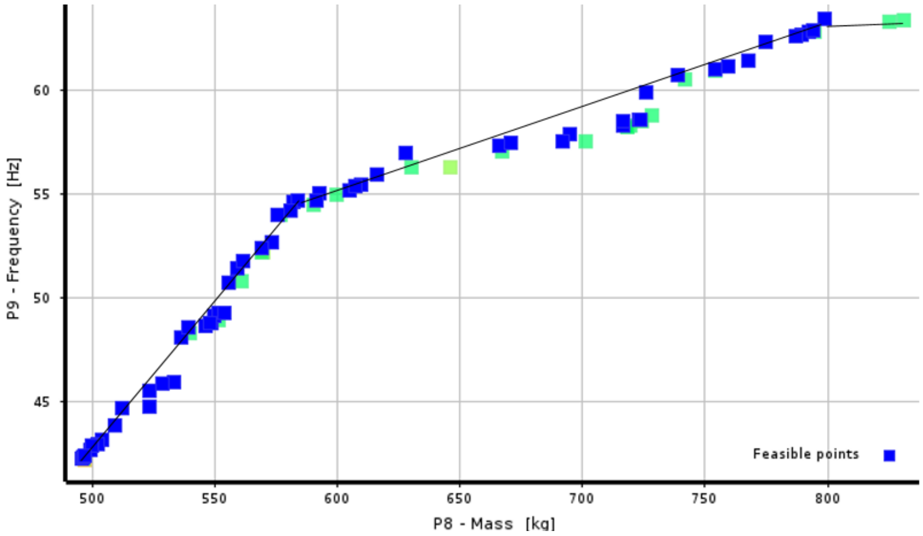

Fig. 13 Pareto solution set

There is no good or bad solution in Pareto solution set, so the designer needs to find the most suitable solution according to his own design. According to Fig. 13, with the increase of the mass of the column, the first-order natural frequency generally shows an increasing trend. An inflection point appears near the mass of 600kg. The selected candidate points and their multiple corresponding design variables are shown in table 7.

Table 7: comparison of optimization results

	P3	P4	P6	P7	Mass	Frequency
Original	1200	20	20	105	678.22	45.986
Optimization	1100	15.047	23.019	119.55	627.87	57.009
Adjustment	1100	15	23	120	628.25	57.238

Considering the actual processing, the final optimization design variable was obtained by rounding the optimized variables, and the finite element model was analyzed by regenerating the design variables. According to the statics analysis results, the maximum deformation of the column is 0.0035mm and the maximum stress is 0.6mpa, which meet the design requirements. The modal analysis results are shown in table 7. Compared with the original design, the optimized column quality decreased by 7.3% and the first-order natural frequency increased by 24.49%. The overall performance of the column has been improved.

5 CONCLUDING REMARKS

Through the performance analysis of a machining center column, it is found that the static performance of the column is good and the dynamic stiffness is insufficient. In order to improve the anti-seismic performance of the machine tool, the first-order natural frequency needs to be increased. In this design, response surface optimization method is used for multi-objective optimization of columns. Experimental design points are generated through central composite design, response surface is generated by gene aggregation method, and finally NSGA-II algorithm is used for optimization. The first-order natural frequency is improved while column quality is reduced, and the optimization effect is good. Because genetic algorithm has good nonlinear optimization ability, this method can be extended to other fields of nonlinear, multi-objective complex system optimization.

REFERENCE

► Bere, Paul; Berce, Petru; Nemes, Ovidiu. (2012). *Phenomenological fracture model for biaxial fibre reinforced composites*, Composites Science and Technology, Vol: 43, Iss: 5, Pages: 2237-2243

► CEN, H.T. (2004). Bionic theory of structure, bionic design of light parts and RP process verification. Beijing university of aeronautics and astronautics, 2004

► Ding, X. H., Zhang, J., Zhang, H. (2019). Multi objective optimization design of iron pad location of three point support T-bed machine tool. China Mechanical Engineering: 1-7 [2019-11-08].

► Kolar, P., Sulitka, M., & Janota, M. (2010). Simulation of dynamic properties of a spindle and tool system coupled with a machine tool frame. The International Journal of Advanced Manufacturing Technology, 54(1-4),11-20. doi:10.1007/s00170-010-2917-7

► Konishberg, F. (1992). Machine tool structure. Beijing: China Machine Press.

► Kurtaran, H., & Erzurumlu, T. (2005).Efficient warpage optimization of thin shell plastic parts using response surface methodology and genetic algorithm. The International Journal of Advanced Manufacturing Technology, 27(5-6), 468-472.doi:10.1007/s00170-004-2321-2

► Li, X.Y., Yin, X. D., Xu, S. L., Cao, Q. Y. (1992). Experimental study on dynamic performance of MS1320 high speed cylindrical grinder. Journal of Hunan University (NATURAL SCIENCE EDITION), 03: 25-31

► Li, Y. P., Ba, C. L., Liu, L. C. (2019). Comprehensive optimization of heavy machine tool column with bionic structure. China Mechanical Engineering, 30 (13): 1621-1625 + 1637

► Myers, A., Ford, D. G., Xu, Q. (2003). Finite element analysis of the structural dynamics of a vertical milling machine. Transactions on Engineering Sciences, 431-440

► Rajesh, R., & Anand, M. D. (2012).The Optimization of the Electro-Discharge Machining Process using Response Surface Methodology and Genetic Algorithms. Procedia Engineering, 38, 3941-3950.doi:10.1016/j.proeng.2012.06.451

► Routara, B. C., Sahoo, A. K., Parida, A. K., & Padhi, P. C. (2012).Response Surface Methodology and Genetic Algorithm used to Optimize the Cutting condition for Surface Roughness Parameters in CNC Turning. Procedia Engineering, 38, 1893-1904.doi:10.1016/j.proeng.2012.06.232

► Selvakumar, S., & Ravikumar, R. (2018). A Novel Approach for Optimization to Verify RSM Model by Using Multi-Objective Genetic Algorithm (MOGA). Materials Today: Proceedings, 5(5), 11386-11394.doi:10.1016/j.matpr.2018.02.106

► Unune, D. R., Nirala, C. K., & Mali, H. S. (2018). ANN-NSGA-II dual approach for modeling and optimization in abrasive mixed electro discharge diamond grinding of Monel K-500. Engineering Science and Technology, an International Journal, 21(3), 322-329.doi:10.1016/j.jestch.2018.04.014

► Wu, J., Wang, J., Wang, L., Li, T., & You, Z. (2009). Study on the stiffness of a 5-DOF hybrid machine tool with actuation redundancy. Mechanism and Machine Theory, 44(2), 289-305. doi:10.1016/j.mechmachtheory.2008.10.001

► Yang, Z. P. (2017). Research on topological optimization and bionic design of column structure of milling compound machining center. 2017

► Yu, H. L., Wang, Y. Q., Chen, H. L., Cun, H. Y. (2012). Optimization of machine tool column parameters based on response surface model and multi-objective genetic algorithm. Journal of Xi'an Jiaotong University, 46 (11): 80-85