LIGHTWEIGHT OPTIMIZATION DESIGN OF HORIZONTAL DOUBLE-SIDED COMBINED MACHINE TOOL BED BASED ON ANSYS WORKBENCH

Tian Xiaoguang[1], Ren Xiaozhong[2], GE Sai[3], Wang Ya-hui[3], Wang Xiao-bo[3]
[1]*College of Mechanic and Electronic Engineering, Huanghe Jiaotong University,*
Jiaozuo, Henan, 454950, China. Email:41028118@qq.com
[2]*Henan University of Science and Technology, Luoyang, China, 471003*
E-mail: ren_xiaozhong@126.com
[3]*School of Mechanical Engineering, North China University of Water Resources and Electrical Power Zhengzhou,*
Henan 450045, China
Email: wangyahui@ncwu.edu.cn

ABSTRACT*: In this paper, the bed mechanism of the horizontal double-sided combined machine tool is taken as the research target. Firstly, the static and dynamic analysis methods are used to simulate the working state. The equivalent stress and deformation distribution are calculated by static analysis of the bed to judge whether it meets the strength and stiffness requirements or not. Through the modal analysis of the machine bed, the first six natural frequencies and modal mode are obtained to study the dynamic characteristics of the bed working state. Furthermore, the response surface optimization module (Response Surface Optimization) included in the optimization design toolbox of ANSYS Workbench software is used to lighten and optimize the bed structure. By comparing the optimization results before and after, the bed quality of the horizontal double-sided combined machine tool is reduced by 3.36% under the condition that the rigidity of the machine tool is improved or not reduced, and the lightweight optimization design of the horizontal double-sided combined machine tool is realized.*

KEYWORDS*: Horizontal double-sided combined machine tool; Characteristic analysis; Response Surface Optimization; Lightweight optimization*

1 INTRODUCTION

The horizontal double-sided combined machine tool is important equipment for manufacturing machine parts in the manufacturing industry. Its applications in the wind power, petroleum, chemical, mold and other mechanical processing manufacturing are more and more extensive (Yu and Tang, 2019). The advancement of horizontal machine tools directly affects the product quality and productivity of the national economic sector, so the optimization of machine tool structure has become particularly significant. The traditional machine tool optimization method generally adopts the classical theory of material mechanics and the designer's own experience to design and improve the key large parts of the machine tool on the existing basis. The disadvantages are simple form, complicated structure, high loss of materials and high cost (Qiu Wenbiao et al. 2018; Yun Qing, 2014). Therefore, it is necessary to carry out lightweight design of the lathe.

Based on the parametric modeling and finite element dynamic as well as static analysis of horizontal double-sided machine tools, this paper optimizes the lightweight and optimized design of horizontal double-sided machine tools. The main contents of the design research are as follows: 1.Using the SolidWorks software to establish a three-dimensional conceptual design model of the horizontal double-sided combined machine tool and complete the assembly of the whole machine. 2. Using ANSYS software to make static structural analysis and modal analysis of the machine bed to determine the optimization direction. 3. Using the response surface optimization module (Response Surface Optimization) in the ANSYS Workbench software and the response surface method to construct the advantages of complex structural function, meanwhile combine the response surface method and the structural optimization energy criterion principle to achieve the workpiece Multi-objective optimization (CHEN Yelin, et al. 2010). In this paper, only the machine bed in the horizontal double-sided combined machine tool is selected as the key research object, which is optimized, and the optimal design scheme is selected to realize the lightweight optimization design of the horizontal double-sided combined machine tool..

2 THREE-DIMENSIONAL STRUCTURE MODELING

The horizontal double-sided combined machine tool consists of five key components: the machine bed, the clamping apparatus, sliding table, headstock and column. The Solid Works 3D modeling software is used to carry out 3D parametric modeling of the horizontal double-sided combined machine tool, and complete the assembly of the horizontal double-sided combined machine tool. The assembly diagram is as shown in Figure 1, and the explosion diagram is as shown in Figure 2.

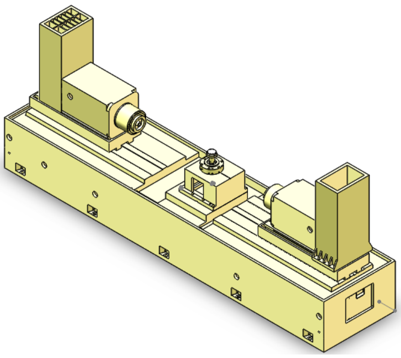


Fig.1 Assembly diagram of Horizontal double-sided combination machine

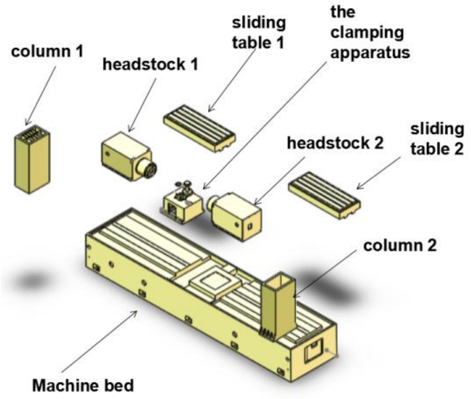


Fig.2 Explosive drawing of Horizontal double-sided combination machine

3 FINITE ELEMENT ANALYSIS OF THE MACHINE BED

In this paper, only the weight optimization operation of the key parts of the machine bed is carried out. Before the optimization, the ANSYS software is used to perform static analysis and modal analysis on the component model to achieve the purpose of simulation of the actual working state, and understand the weak parts of the component design, as well as to determine Optimize the direction.

ANSYS is large-scale general-purpose finite element analysis software that integrates structure, fluid, electric field, magnetic field and sound field analysis. It is developed by ANSYS Company of the United States and widely used in many fields, such as machinery manufacturing, civil engineering, and automobile transportation. Related product designs and methods provide a detailed and detailed reference (FANG Peng et al. 2013; Wei Yabin, et al.2018).

Please follow the instructions in this template.

3.1 Static analysis of the machine bed

By setting the cell properties of the finite element model of the frame, Gray Cast Iron (HT300) was selected as the material. According to the properties of gray cast iron, the corresponding material property parameters are set (Son H, 2010)as shown in table 1:

Table 1. Material property attribute

Material	Density (kg/m³)	Poisson's ratio	Elastic Modulus (GPa)
HT300	7850	0.269	209

Since the machine bed is subjected to gravity in actual work, the machine bed base is fixed to the ground, so full restraint is applied to the bottom surface of the machine bed. Since this paper only studies the gravity load of all the components supported by the machine bed and the additional working force generated during the working process, according to the empirical formula of the cutting force, the cutting force generated by the drilled steering bearing can be calculated when the machine bed machining workpiece:

$$F_f = C_{F_f} d^{2 z_{F_f}} f^{y_{F_f}} K_{F_f} \tag{1}$$

Where, C_{Ff} is the correction factor; d is the tool diameter; f is the feed amount; K_{Ff} is the total correction factor.

According to the mechanical process manual, the machining tool and the workpiece material, take C_{Ff}=1400, Z_{Ff}=0.5, y_{Ff}=0.7, K_{Ff}=1, and bring into the formula 1 to obtain the drilling force:

$$F_f = 600 \times 32 \times 0.4^{0.7} \times 1 \approx 10109 \quad N \tag{2}$$

The drilling force generated by the machine tool during machining is obtained to be 10109N, so the constraint is set as: the workpiece gravity in the negative direction of Y-axis is 3.2t; the workpiece's gravity acceleration is 9.8m/s^2;the cutting force produced by the workpiece during work is 10109N.

Set up the above series of pre-simulation processing and solve the problem. The analysis results show that the overall deformation cloud diagram of the machine bed is as shown in Figure 3, and the equivalent stress cloud diagram of the machine bed is as shown in Figure 4.

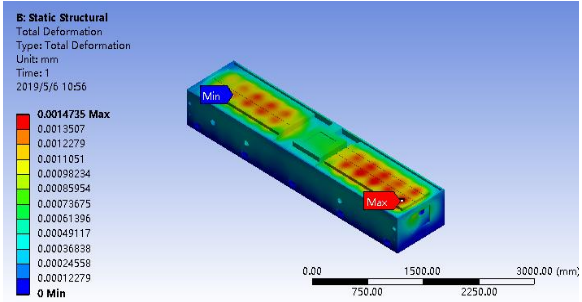


Fig. 3 Total Deformation cloud diagram of the machinebed

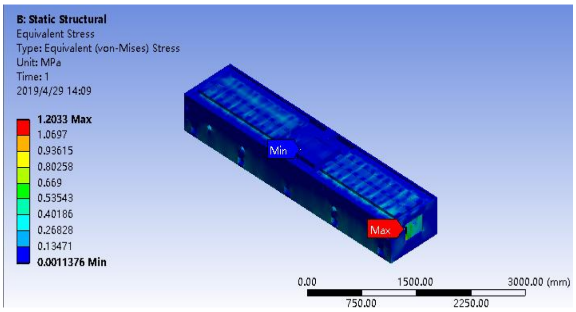


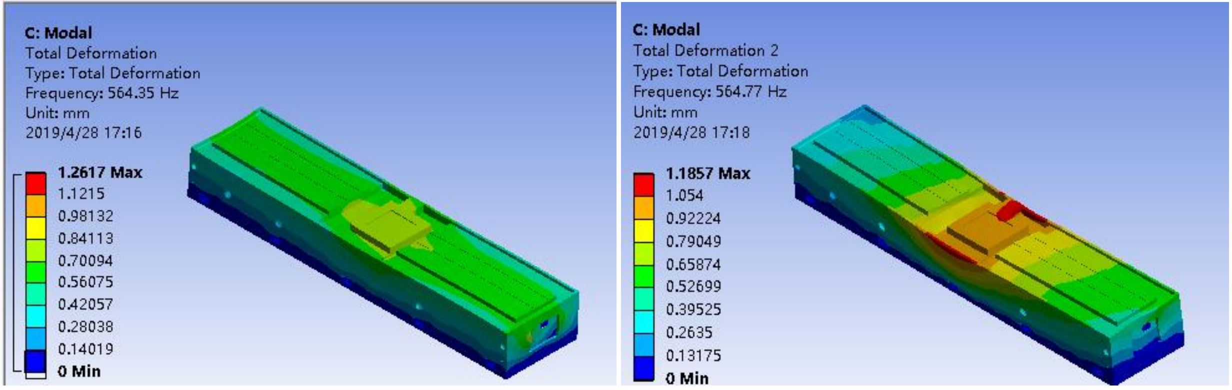
Fig. 4 Equivalent Stress cloud diagram of the machine bed

According to the deformation cloud diagram of the machine bed of Fig.3, the maximum deformation position of the machine bed is at the joint of the guide rail and the rib, besides that the maximum deformation is about 1.4735um. The method of changing the rib layout or the thickness of the rib at this position can be used to improve the static performance of the machine bed and improve the capacity of the carrying table. According to the Equivalent stress cloud diagram of Fig.4, under the action of load, the maximum stress of the machine bed structure is 1.20Mpa at the rib plate, and the tensile limit of the gray cast iron material is 300Mpa, which meets the strength requirement within the allowable range of stress.

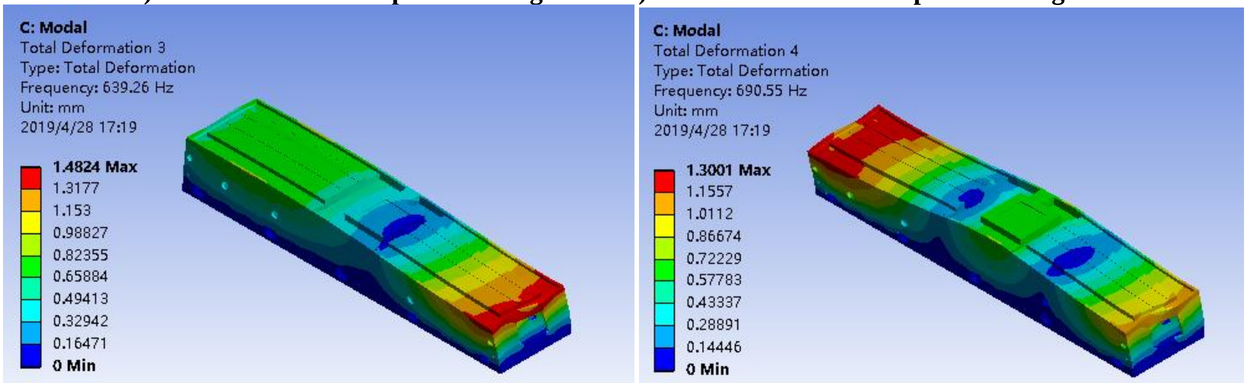
3.2 Modal analysis of the machine bed

Modal analysis is a method to study the dynamic characteristics of structures. The inherent vibration characteristics of machine components are calculated and analyzed by finite element software. According to the calculated modal parameters of the specific natural frequency, damping ratio and mode shape of each modality, the vibration characteristics of the component are analyzed to find the weak link of the structure to determine the optimization direction (Zhang Yan.2014; Hull P V .2006.)

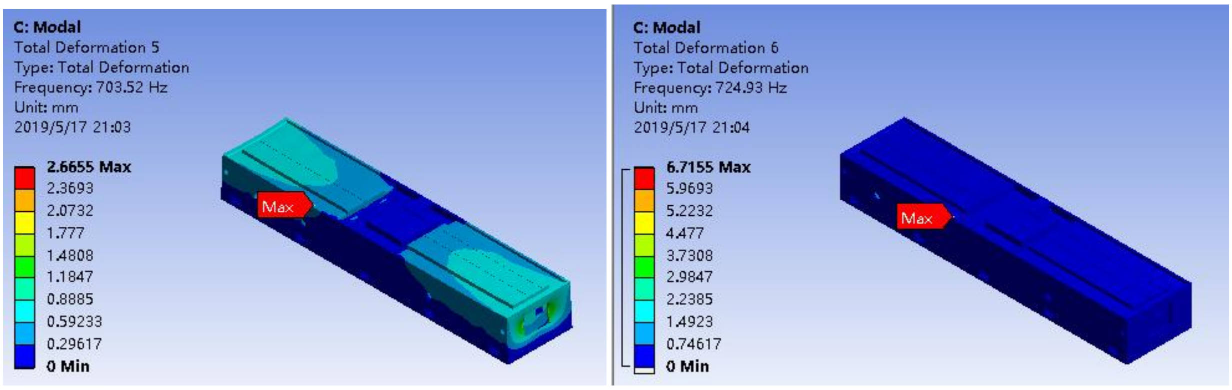
The modal analysis of the machine bed is carried out, and the first six modal parameters are extracted to analyze the dynamic characteristics of the frame, meanwhile the maximum deformation of the frame at various frequency frequencies can be obtained (Li Qihao, 2003). The first six-order modal analysis of the machine bed is obtained. Analyze the vibration mode cloud diagram as shown in Figure 5:



a)First order mode shape cloud diagram b)Second order mode shape cloud diagram



c) Third-order mode shape cloud diagram d) Fourth-order mode shape cloud diagram



e) Fifth-order mode shape cloud diagram f) Sixth-order mode shape cloud diagram

Fig. 5 Sixth-order vibration pattern of the machine bed

From the modal analysis results of the machine bed, the six-order natural frequency and vibration mode characteristics of the machine bed are known, as shown in Table 2 below:

Table 2. Analysis of the sixth-order modal results of the machine bed

Order	Natural Frequency (Hz)	Maximum Deformation (mm)
1	564.35	1.2617
2	564.77	1.1857
3	639.26	1.4824
4	690.55	1.3001
5	703.52	2.6655
6	724.93	6.7155

According to the first six-order mode shape cloud image of the machine bed of Fig. 5 and the modal analysis results in Table 2, it can be concluded that the dynamic and static performance stiffness of the machine bed is insufficient. The deformation performance is characterized by the twisting and vibration of the left and right sides of the machine bed, meanwhile the above-mentioned defects can be repaired by optimizing the size and structure of the machine bed ribs, thereby obtaining the improvement of the overall structural steel of the machine tool.

4 RESPONSE SURFACE METHOD LIGHTWEIGHT DESIGN OF THE MACHINE BED

The horizontal double-sided combined machine tool designed in this paper is required to have suitable static stiffness, strong anti-interference performance and small deformation. Therefore, in order to achieve the required performance, this paper also needs to consider the two aspects of reducing the maximum deformation amount and increasing the natural frequency while reducing the weight of the horizontal double-sided combined machine bed. Hence, the material, wall thickness and size of each part of the machine tool are optimized under the requirements of the triple optimization target.

The response surface method model optimization process mainly includes: a parametric model module, a response surface module and an optimization module. After the parametric model is established, the experimental design method is used to obtain the sample data. Using the regression analysis technique, the complex implicit relationship between the response value and the design variable is approximated by the display function, and the response surface model is obtained. Optimization iteration based on response surface model can avoid calling simulation model every time, thus improving computational efficiency (Jiang Heng et al. 2011)

As a mathematical statistical processing method, the response surface method is used to solve the multivariate problem. It integrates experimental design and mathematical statistics, and models as well as analyzes the model. The relationship between design variables and response values implied in the optimization problem can be expressed through intuitive mathematical expressions(SHAOYinghe,2018).The mathematical expression used to judge the pros and cons of the design scheme is the objective function in the optimization design. The optimization design is to find the optimal scheme from the many feasible designs and the criteria of the objective function (Zhang Zaifang, 2018).Using the optimal design theory method, under the constraints of constraints and design variables, the structural parameters are iterated, and finally the optimal solution is found.

The optimized design mathematical model can be expressed as follows:

Objective function:

$$F = F(x_1, x_2, x_3, \dots, x_n) \tag{3}$$

Design variable selection range:

$$\min(x_i) < x_i < \max(x_i) \quad (i = 1,2,\ldots,N) \tag{4}$$

Restrictions:

$$\min(g_j) < g_j < \max(g_j) \quad (j = 1,2,\ldots,M) \tag{5}$$

Where, F represents the objective function; xi represents the design variable; N is the number of design variables; gi is the state variable; and M is the number of state variables.

In this paper, the overall workpiece quality is reduced as the final optimization goal; the structural parameter optimization method is selected; and the product structure size and load are selected as the optimization parameters to reduce the workpiece deformation and increase the natural frequency as the objective function; taking the workpiece weight as low as possible for constraint conditions and using the optimization algorithm, the iterative calculation formula, finally the optimal size parameters is found out.

4.1 Select design variables

When optimizing the machine bed of the horizontal double-sided combined machine tool, the static performance analysis results of the previous bed body can be taken as references. The parameters are used as design variables to optimize the design of the machine bed (Zhang Huanmei, 2018), such as the thickness of the ribs and the size of the weight reduction holes. The 3D solid model of the machine bed constructed according to the actual structural parameters in the SolidWorks software is imported into the ANSYS Workbench, and the optimized variables are associated with the ANSYS software to define the optimized variables. Defining the machine bed transverse rib thickness dimension parameter name is DS_D01; the weight reduction hole length parameter name is DS_D02; the weight reduction hole width parameter name is DS_D03; and the bed wall thickness size parameter name is DS_D04.After the definition, the model is imported into ANSYS, and the required optimization parameters as well as the optimization target object are selected to establish an analysis project.

4.2 Establish an optimized mathematical model

1. Design variable

The structural size of each part of the original machine bed is taken as the initial reference value, and the reasonable variable range is defined in combination with the machine bed process and structure. The detailed definition of the optimization variables is as shown in Table 3:

Table 3. Optimized design variables for various parts of the machine bed structure

Parameter	Variable name	Initial value (mm)	Design interval (mm)
Rib thickness	DS_D1	18	13-23
Weight reduction hole length	DS_D2	120	110-130
Weight reduction hole width	DS_D3	100	90-110
Bed wall thickness	DS_D4	25	20-30

1. Mathematical model

$$\begin{gathered} \text{Min } f_1(x); \\ \text{Max } f_2(x); \\ \text{s.t. } \text{mass} \le 0 \\ 13 \le x_1 \le 23 \\ 110 \le x_2 \le 130 \\ 90 \le x_3 \le 110 \\ 20 \le x_4 \le 30 \end{gathered} \tag{6}$$

Where, $f_1(x)$ represents the maximum deformation amount;

$f_2(x)$ represents the first natural frequency; mass represents the difference between the masses before and after optimization;

x_1 represents the thickness of the rib;

x_2 represents the length of the weight reduction hole;

x_3 represents the width of the weight reduction hole;

x_4 indicates the wall thickness of the bed.

Because the optimization goal of this paper is to reduce the machine bed body mass while maximizing the static stiffness of the machine bed, the machine bed deformation, mass and first-order natural frequency are selected as optimization objects.

For the optimized part, the higher the natural frequency is, the better its stiffness performance is. Therefore, the objective function Max $f_2(x)$ is established, and the stiffness of the part is improved by increasing the natural frequency. At the same time, the target function Min $f_1(x)$ is used to control the deformation of the device as small as possible, and the constrained condition mass≤ 0 is used to achieve the goal of device weight reduction. The rest of the constraints on optimizing the design variables are based on the machine bed process and structure.

4.3 Optimization process and result analysis of the machine bed

Based on the ANSYS software optimization design toolbox (Design Exploration), the machine bed of the horizontal double-sided combination machine tool is lightweight optimized. Use the Response Surface Optimization module included in the ANSYS Optimization Design Toolbox. Through the ANSYS target optimization design process, the machine bed is analyzed and calculated to obtain the optimal value. The response surface optimization design first sets the optimization parameter variable to obtain a large sample space of an optimization variable, and obtains a large number of data points in the initial stage of optimization, and then optimizes the parameters (Cong Ming et al. 2011).The design point sample space is as shown in Table 4:

Table 4. Design samples and numerical simulation results

serial number	D1	D2	D3	D4	weight(t)	Deformation(mm)	frequency(Hz)
1	19.00	120.00	100.00	25.00	3.26	0.001476	565.09
2	13.00	120.00	100.00	25.00	3.13	0.001626	571.40
3	25.00	120.00	100.00	25.00	3.26	0.001477	565.04
4	19.00	110.00	100.00	25.00	3.26	0.001473	564.57
5	19.00	130.00	100.00	25.00	3.26	0.001479	561.29
6	19.00	120.00	90.00	25.00	3.27	0.001464	563.57
7	19.00	120.00	110.00	25.00	3.26	0.001489	560.61
8	19.00	120.00	100.00	22.50	3.25	0.001491	564.92
9	19.00	120.00	100.00	27.50	3.27	0.001470	565.30
10	14.77	112.96	92.96	23.24	3.17	0.001544	569.24
11	23.23	112.96	92.96	23.24	3.26	0.001468	564.07
12	14.77	127.04	92.96	23.24	3.17	0.001543	568.92
13	23.23	127.04	92.96	23.24	3.25	0.001465	565.17
14	14.77	112.96	107.04	23.24	3.17	0.001572	568.73
15	23.23	112.96	107.04	23.24	3.25	0.001481	564.97
16	14.77	127.04	107.04	23.24	3.16	0.001562	561.75
17	23.23	127.04	107.04	23.24	3.25	0.001486	558.17
18	14.77	112.96	92.96	26.76	3.19	0.001523	568.99
19	23.23	112.96	92.96	26.76	3.28	0.001454	564.16
20	14.77	127.04	92.96	26.76	3.19	0.001522	569.11
21	23.23	127.04	92.96	26.76	3.27	0.001460	565.39
22	14.77	112.96	107.04	26.76	3.18	0.001556	569.14
23	23.23	112.96	107.04	26.76	3.27	0.001470	565.07
24	14.77	127.04	107.04	26.76	3.18	0.001557	562.16
25	23.23	127.04	107.04	26.76	3.26	0.001480	558.48

The relationship between design points and machine bed quality is as shown in Figure 6:

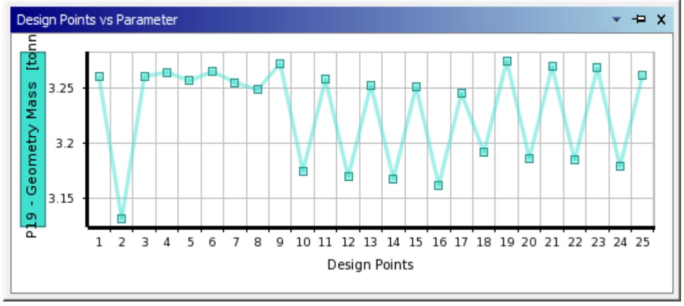
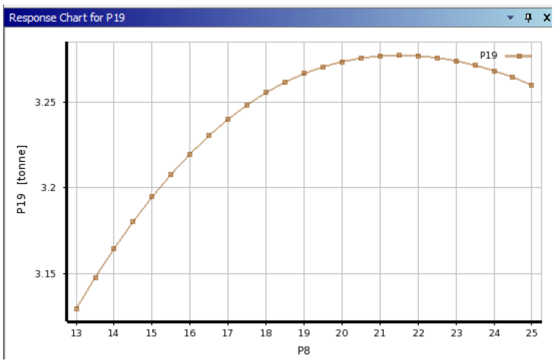


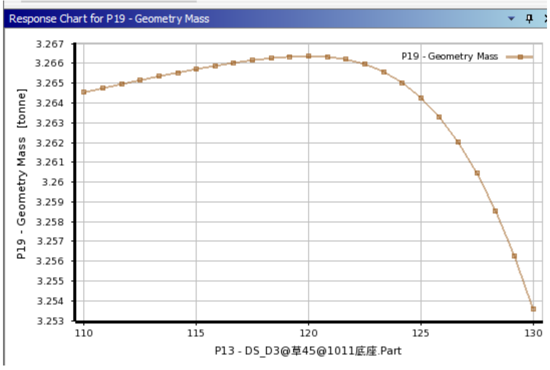
Fig. 6 Schematic diagram of design point and machine bed quality

The change of each size parameter will affect the objective function value of the machine bed optimization. The effect of each parameter on the objective function is observed by looking at the response curve of each response parameter of the response surface analysis module.

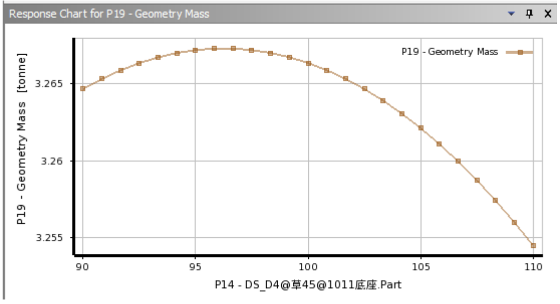
The 2D curve of the machine bed quality as a function of the machine bed structure size parameters is asshown in Figure 7.



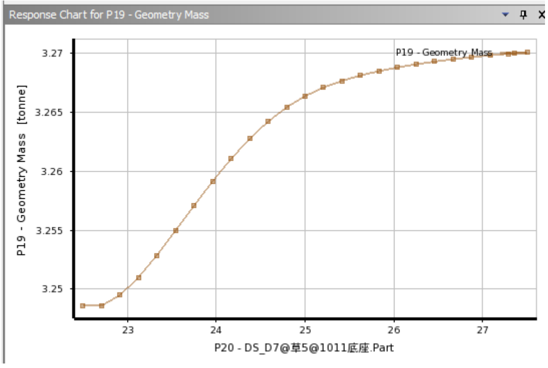
a) DS_D1 parameter response curve change diagram



b) DS_D2 parameter response curve change diagram



c) DS_D3 parameter response curve change diagram

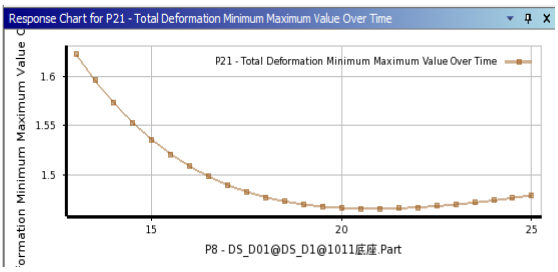


d) DS_D4 parameter response curve change diagram

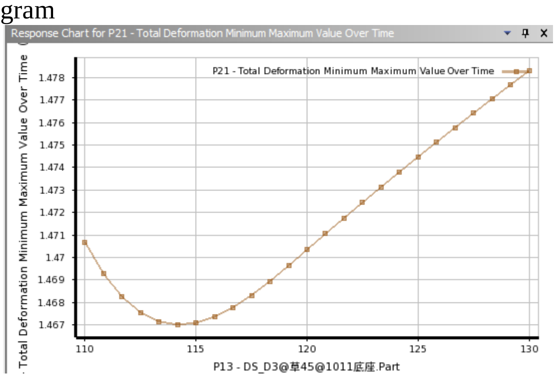
Fig. 7 Weight with size parameter variable response change diagram

It can be seen from the change of weight and size parameter variable response that the influence of machine bed weight on the three parameters of the horizontal rib thickness, while the weight loss hole length and the weight loss hole width of the machine bed is first increased and then decreased; The thickness of the machine bed is proportional to the thickness of the machine bed, the thicker the machine bed wall, then the greater the weight of the machine bed.

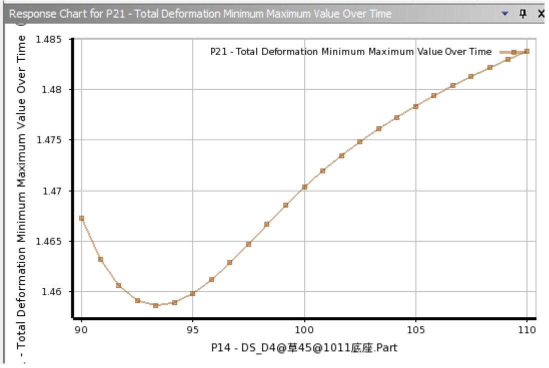
The maximum deformation of the machine bed and the natural frequency of the first order with the response curve of each size variable are as shown in Figure 8 and Figure 9:



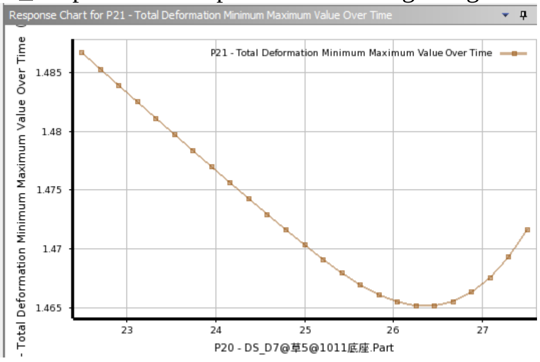
a) DS_D1 parameter response curve change diagram



b) DS_D2 parameter response curve change diagram

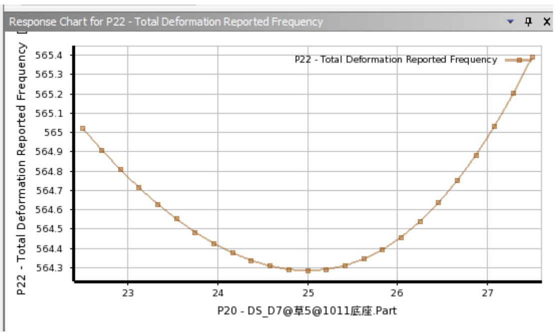


c) DS_D3 parameter response curve change diagram

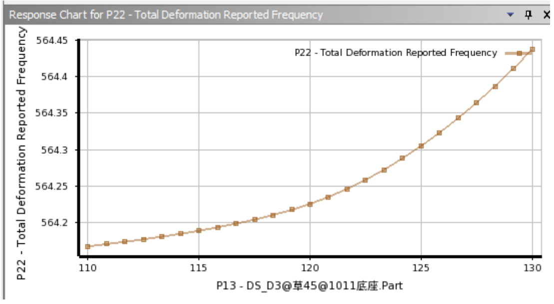


d) DS_D4 parameter response curve change diagram

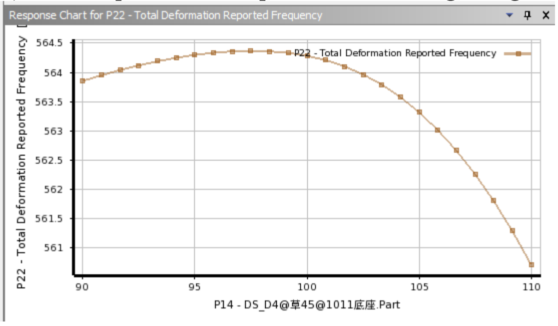
Fig. 8 Maximum deformation with size parameter variable response change diagram



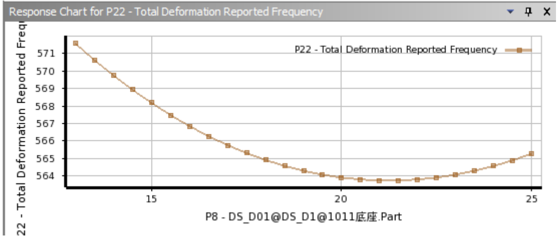
a)DS_D1 parameter response curve change diagram



b) DS_D2 parameter response curve change diagram



c)DS_D3 parameter response curve change diagram



d)DS_D4 parameter response curve change diagram

Fig. 9 Natural frequency with size parameter variable response change diagram

Through the above dimensional parameters to optimize the response curve of each objective function, it can be known that the influence of bed deformation on the four size parameters is first reduced and then increased. The natural frequency of the first step of the machine bed decreases first and then increases as the thickness of the ribs and the wall thickness of the bed increases. It increases as the length of the weight reduction hole increases, and decreases as the width of the weight reduction hole increases.

One of the important indicators for analyzing the sensitivity of the machine bed when analyzing the machine bed optimization results. It means that, the sensitivity of structural performance parameters to changes in design variables, and the effects of different size parameters on the performance of each target optimization function of the machine bed are different (NI Xiao-yu,et al.2005).The sensitivity analysis of each size parameter for each optimized target of the machine bed is as shown in Figure 10.In the figure, the red indicator represents the DS_D01 parameter (the bed transverse rib thickness dimension); the yellow indicator represents the DS_D02 parameter (the weight reduction hole length dimension); the green indicator represents the DS_D03 parameter (the weight reduction hole width dimension); and the blue indicator represents the DS_D04 parameter (Bed wall thickness size).It can be seen from the figure that the design parameters that have the greatest influence on the quality, meanwhile the maximum deformation of the machine bed and the natural frequency are the DS_D01 bed transverse rib thickness. Among them, the impact on the maximum deformation of the bed is the biggest.

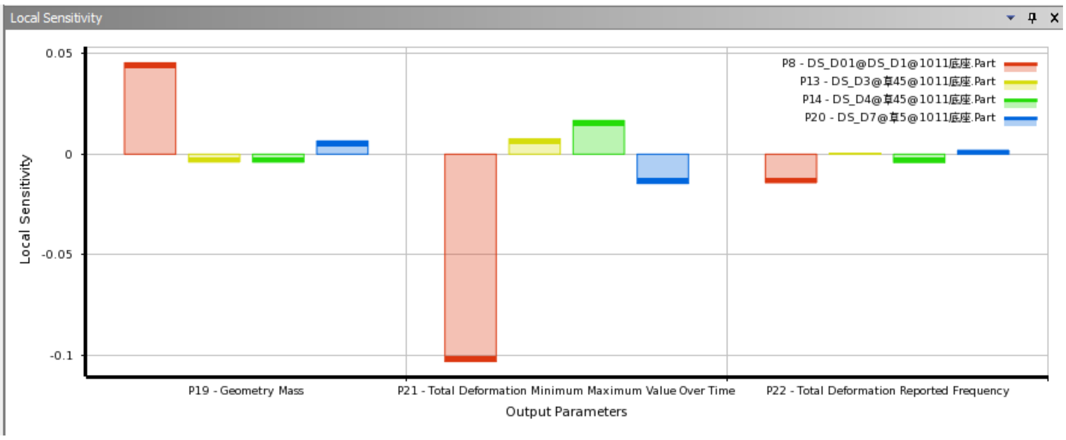


Fig. 10 sensitivity analysis of each size parameter for each bed optimization target

Set the constraint boundary value and find the optimal result as shown in Figure 11:

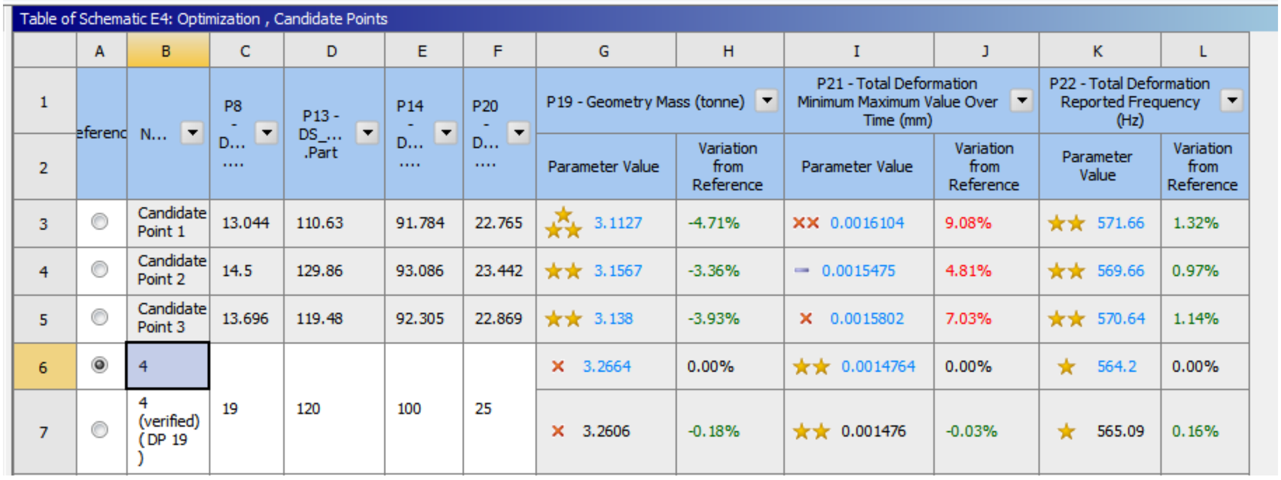
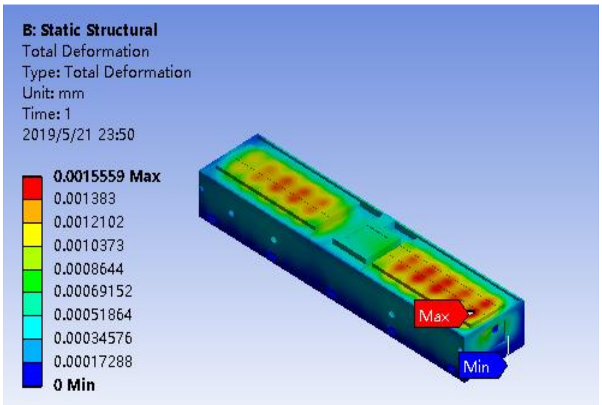


Table of Schematic E4: Optimization , Candidate Points

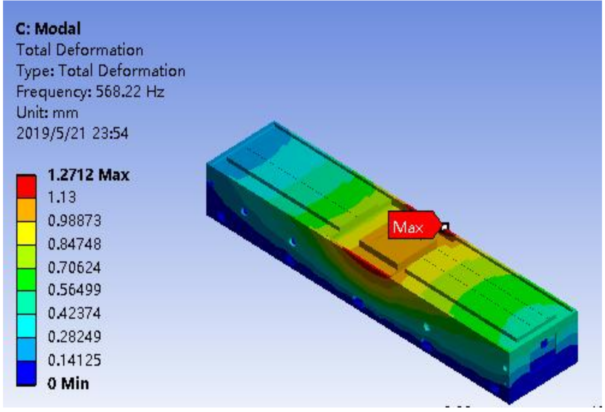
	A	B	C	D	E	F	G	H	I	J	K	L
1	eferenc	N...	P8 - D...	P13 - DS_... .Part	P14 - D...	P20 - D...	P19 - Geometry Mass (tonne)		P21 - Total Deformation Minimum Maximum Value Over Time (mm)		P22 - Total Deformation Reported Frequency (Hz)	
2							Parameter Value	Variation from Reference	Parameter Value	Variation from Reference	Parameter Value	Variation from Reference
3	○	Candidate Point 1	13.044	110.63	91.784	22.765	★★★ 3.1127	-4.71%	✕✕ 0.0016104	9.08%	★★ 571.66	1.32%
4	○	Candidate Point 2	14.5	129.86	93.086	23.442	★★ 3.1567	-3.36%	– 0.0015475	4.81%	★★ 569.66	0.97%
5	○	Candidate Point 3	13.696	119.48	92.305	22.869	★★ 3.138	-3.93%	✕ 0.0015802	7.03%	★★ 570.64	1.14%
6	●	4	19	120	100	25	✕ 3.2664	0.00%	★★ 0.0014764	0.00%	★ 564.2	0.00%
7	○	4 (verified) (DP 19)					✕ 3.2606	-0.18%	★★ 0.001476	-0.03%	★ 565.09	0.16%

Fig. 11 Optimized candidate point diagram

The model is re-modeled according to the optimized size parameters, and the optimized finite element analysis results of the machine bed are asshown in Figure 12:



a) deformation cloud map of the machine bed



b)First-order vibration mode of the machine bed

Fig. 12 Optimized bed finite element analysis results

After setting the machine bed size parameter, the optimized size and target parameter values are compared with the original parameters, as shown in Table 5:

Table5.Optimization before and after comparison table of the bed

design variable	Before	after	Rate of change (%)
Rib thickness(mm)	18	14.5	-19.4
Weight reduction hole length(mm)	120	130	+8.3
Weight reduction hole width(mm)	100	93	-7
Bed wall Thickness(mm)	25	23.5	-6
Bed weight(kg)	3260.6	3156.7	-3.36
Bed deformation(μm)	1.4735	1.547	+4.81
First-order vibration mode (Hz)	564.35	569.66	+0.97

From the comparison results in Table 5, after optimization, the machine bed weight is reduced by 3.36% compared with the original; the maximum deformation of the machine bed is reduced by 0.39%;and the first natural frequency of the machine bed is increased by 0.15%.The optimization results show that under the premise that the weight of the bed is significantly reduced, the dynamic and static performance index of the lathe bed has also been improved to a certain extent, achieving the goal of lightweight optimization of the machine bed.

5 CONCLUSION

In this paper, the horizontal double-sided combined machine tool bed is taken as the research object. Firstly, the finite element static analysis and modal analysis are carried out to simulate the dynamic and static working state. According to the equivalent stress cloud diagram, displacement deformation cloud diagram and the first six order shape cloud diagram of the simulation results, the maximum equivalent stress, maximum shape variable, natural frequency and deformation amount of each order are calculated; the weak links in the design of the components are determined; and then the response surface method is used to optimize the design. By comparing the finite element analysis data before and after bed optimization, the maximum deformation of the lathe bed is reduced by 0.39% and the first-order natural frequency is increased by 0.15% on the premise that the machine bed quality is reduced by 3.36%. The feasibility of the lightweight design of the machine bed was verified, and the lightweight design of the horizontal double-sided machine tool was completed.

6 AKNOWLEDGEMENT

Training Plan for Young backbone Teachers of Colleges and Universities in Henan (2018GGJS194); Engineering Research Center on Intelligent Manufacturing Technology and Equipment in Henan. And the project was supported by a key research project of Higher Education of Henan Province (20A460019).

7 REFERENCES

►CHEN Yelin, DING Xiaohong, GUO Chunxing, et al. 2010,Optimization design method of machine bed structure. Mechanical Design, 27(8): 65-68.

►Cong Ming , Han Wei , Zhao Qiang , et al. 2011, Finite Element Analysis of High Speed Horizontal Machining Center Slide Based on Combination. China Mechanical Engineering, 22(13): 1527-1531.

►FANG Peng, LI Jian, WEI Liao. 2013, Finite Element Analysis of Machine Tool Spindle Based on ANSYS Workbench.Equipment manufacturing technology, (4):28-30.

►Jiang Heng, Guan Yusheng, Qiu Zhicheng, et al. 2011,Dynamic and static multi-objective optimization of vertical machining center based on response surface method. Journal of Mechanical Engineering, 47(11): 125-133.

►Hull P V , Canfield S .2006, Optimal Synthesis of Compliant Mechanisms Using Subdivision and Commercial FEA. Journal of Mechanical Design, 128(2):337.

►Li Qihao, Zhang Chunlai. 2003, Application of Optimization Technology in CAE in ANSYS Software. Manufacturing Automation. (9): 35-39.

►NI Xiao-yu, YI Hong, TANG Wen-cheng, et al. Finite Element Analysis and Optimization of Machine Tool Bed Structure. Manufacturing Technology and Machine Tools, 2005(2): 47-50.

►Qiu Wenbiao, Zhang Jianfu, Yu Dingwen, et al. 2018, Research on Machine Tool Structure Optimization Design Based on Multi-Objective. Combined Machine Tool & Automatic Processing Technology, (2):51-56.

►SHAO Yinghe, HONG Rongjing, YU Chunjian. 2018, Modification of machine bed dynamics model based on response surface method. Combined Machine Tool & Automatic Processing Technology, 537(11): 31-34.

►Son H , Choi H J, Park H W. 2010, Design and dynamic analysis of an arch-type desktop reconfigurable machine. International Journal of Machine Tools and Manufacture, 50(6):575-584.

►Wei Yabin, Yin Guofu, Peng Yu, et al. 2018, Dynamic and Static Performance Analysis of Precision Horizontal Machine Based on ANSYS Workbench. Machinery, 45(05):29-32+59.

►Yu Shaojie, Tang Wuxiang, 2019. Forecast of the Development Trend of CNC Machine Tool Industry in China. Contemporary Economy, 493(01): 24-29.

►Yun Qing. 2014, Key multi-objective optimization design of precision horizontal machining center. Tianjin University,10-13.

►Zhang Huanmei, Guo Yujun. 2018, Finite Element Analysis and Lightweight Design of Machine Tool Box. Journal of North University of China(Natural Science Edition), 39(06): 69-75.

►Zhang Yan. 2014, ANSYS Workbench 15.0 finite element analysis from entry to proficiency. Beijing: Mechanical Industry Press: 90-99.

►Zhang Zaifang, Zhang Jiaxiang. 2018, Optimization of CNC Machine Tool Based on Response Surface Model and Integration Method. Combined Machine Tool and Automatic Machining Technology,(03):14-18.