

Optimization Design of Machine Tool Beam based on Orthogonal Experiment

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Abstract

To enhance the natural frequency of the machine tool beam system and ensure its structural performance, it is crucial to achieve a rational layout of rib structural characteristics. This study utilized the 3D design software SolidWorks for the construction of a three-dimensional model of the machine tool beam, followed by comprehensive modal analysis using Ansys finite element analysis software. In assessing the design merits of the machine tool beam, this research selected the natural frequency as the key objective function and considered initial design variables such as the number of rib segments, rib thickness, rib width, and intermediate span distance for systematic multi-objective optimization design. To determine the optimal combination of design variables, orthogonal experimental design was employed, comprising four factors and three levels. Through rigorous data analysis methods, critical factors influencing beam performance and their optimal levels were identified, thereby establishing an optimal experimental simulation scheme. Subsequent to obtaining the optimal solution, this study further developed a response surface regression model aimed at achieving lightweight design while maintaining static and dynamic beam performance, thereby balancing quality and performance. By employing this research methodology, the study not only provides a scientific basis for optimizing the design of machine tool beams but also offers valuable insights for research and practice in related fields. Results indicate that the optimal configuration-"outer wall thickness of 48mm, rib thickness of 36mm, rib width of 37mm, 9 segments, and intermediate support distance of 690mm"-improved the first-order natural frequency by 23% compared to the original design. Compared to the optimized data post orthogonal experiments, the mass was reduced by 3.6%. This study expands the application scope of orthogonal experimental design and response surface testing, providing beneficial methodological references for the design of other machine tool components.

Keywords

Crossing Beam; First Order Frequency; Orthogonal Experimental Method; Response Surface.

1. Introduction

Machine tools constitute the cornerstone of modern manufacturing systems, serving as critical enablers for precision production across strategic industries such as automotive, aerospace, and renewable energy [1]. Their structural design fundamentally governs both static characteristics (resistance to elastic deformation under operational loads) and dynamic characteristics (response to time-varying cutting forces), which collectively determine machining accuracy and stability [2,3]. With the advent of Industry 4.0, more efficient and precise machine tools have become an inevitable

trend in machine tool development. As a key component of machine tools, the machine tool beam directly affects the overall machining performance and plays an important role in the machining quality and accuracy of the workpieces.

Liu Qiang et al. conducted a finite element study on the beam of a gantry machining center and performed data analysis on the parameters of the contact surfaces that affect the beam's overall dynamic characteristics [4]. Zhao et al. optimized the beam of a gantry machine tool using biomimicry, inspired by the biological structure of leaf ribs, to achieve weight reduction [5]. Ma et al. [6] proposed a method for dynamic modeling and design of machine tools using parallel artificial neural networks and genetic algorithms. Che Zhongwei et al. utilized ANSYS software for static characteristic analysis of the beam, followed by optimization based on the results to achieve lightweight and high-precision objectives [7]. Liu Jie et al. based on ABAQUS computational analysis, identified the main deformation direction of the G3015 machine tool beam, and increased the number of ribs to enhance the overall stiffness, resulting in an increase in the first natural frequency [8].

In this paper, an orthogonal experimental design method is used for the optimization design of the machine tool beam. The design and analysis focus on the number of ribs, rib thickness, rib width, and the supporting structure of the intermediate span. The experimental data are processed using range analysis and variance analysis to select the best parameter combination. The design is then validated using response surface methodology and regression models, yielding data that balance quality and performance, thereby enhancing the overall performance of the beam.

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2. Theoretical Calculation of Vibration Deformation of Machine Tool Beam

The machine tool beam, as the main bearing structure of the machine tool, supports the weight of key components such as the saddle, spindle box, and ram. When subjected to significant operational loads, the beam is often at risk of bending deformation, which poses a direct and non-negligible threat to the overall machining accuracy of the machine tool.

To further investigate the dynamic characteristics of the beam and explore effective optimization strategies, this study is based on the fundamental theoretical framework of mechanical vibration theory. By considering the specific load conditions that the beam experiences in its actual working environment, a dynamic model of the beam's vibration is developed. As shown in Figure 1, the model fully takes into account the structural characteristics, material properties, and the complexity of the working load on the beam. The aim is to provide a solid theoretical foundation for the dynamic performance evaluation and structural optimization of the beam through systematic theoretical analysis.

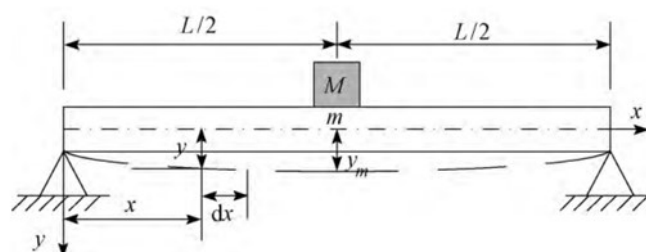


Figure 1. The Vibration Dynamics Model

According to the principles of material mechanics, the approximate differential equation expression for the deflection curve of the vibration system is:

$$\frac{d^2W}{dx^2} = \frac{M}{EI} \quad (1)$$

In this equation, the bending moment M is a function of x , E is the material's modulus of elasticity, and I is the moment of inertia of the cross-section.

Multiplying both sides of Equation (1) by dx and integrating results in the equation for the rotation angle:

$$\theta = \frac{dw}{dx} = \int \frac{M}{EI} dx + C \quad (2)$$

Next, multiplying both sides of Equation (2) by dx and integrating results in the equation for the deflection curve:

$$w = \iint \left(\frac{M}{EI} dx \right) dx + Cx + D \quad (3)$$

In the equations, C and D are constants of integration. Based on Equations (1) to (3), the displacement expression at a distance x from the support in the beam system model is:

$$y = \frac{mg}{48EI} (3L^2x - 4x^3) = y_m \frac{3L^2x - 4x^3}{L^3} \quad (4)$$

Where y_m is the deflection at the midpoint:

$$y_m = \frac{mgL^3}{48EI} \quad (5)$$

For the machine tool beam, the moment of inertia $I = 0.258 \text{ m}^4$ is obtained from SolidWorks. The other values are as follows: the mass of the intermediate saddle tool holder assembly $M = 2609 \text{ kg}$; the modulus of elasticity of the beam material $E = 200 \text{ GPa}$; the weight of the beam $m = 1491 \text{ kg}$; and the length of the beam $L = 1671 \text{ mm}$. The calculated deflection is:

$$y_m = 75.69 \mu\text{m}$$

3. Finite Element Analysis of the Original Machine Tool Beam

After the design domain of the machine tool structure is determined, the static and dynamic optimization model can be established by using the topology optimization theory of the continuum structure.

3.1 Establishment of the Finite Element Model for the Beam Section

In this study, a solid model was established using the three-dimensional drawing software SolidWorks. To improve the analysis speed, some parts of the structure were simplified. After modeling the beam

and load sections, the x_tfile was imported into ANSYS for further finite element analysis. The material was set as structural steel with a density of 7850 kg/m³, Poisson's ratio of 0.3, and Young's modulus of 200 GPa. Figure 2 shows the model body, and Figure 3 shows the finite element model after mesh division, with 448,697 nodes and 215,039 elements. Figure 4 illustrates the flowchart for the optimization design of the machine tool beam.

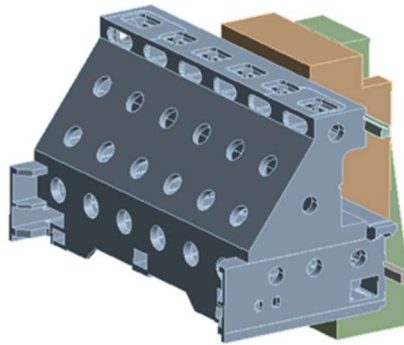


Figure 2. Simplified Finite Element Model of the Beam

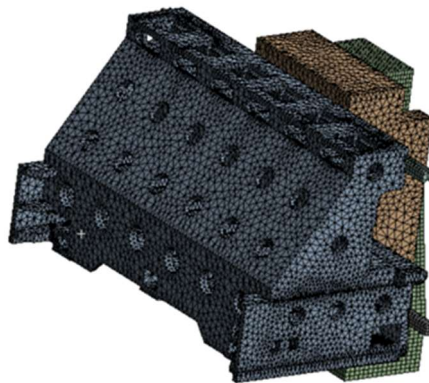


Figure 3. Beam Mesh Division Model

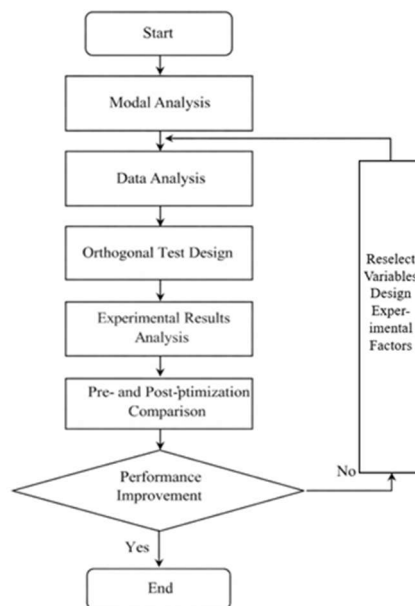


Figure 4. Experimental Flowchart

3.2 Modal Analysis of the Original Machine Tool Beam

During the actual operation of the machine tool, especially during the transient process of startup or shutdown, excitation forces are generated. These forces can trigger vibrations in the overall structure of the machine tool. Such vibrations have a significant impact on the machining accuracy of the machine tool. When the vibration amplitude exceeds a preset threshold, it not only reduces machining accuracy but may also cause long-term damage to the overall performance and service life of the machine tool.

Therefore, this study uses the modal analysis module in ANSYS software to conduct a detailed modal analysis of the machine tool beam. Modal analysis is an important tool based on vibration theory, capable of accurately predicting the natural frequencies and corresponding vibration modes of a structure in free vibration. Through modal analysis, we can effectively avoid resonance phenomena caused by external loads that are close to the natural frequency of the machine tool during operation, thus ensuring the stability and machining accuracy of the machine tool.

As shown in Figure 1, the beam is subjected to its own weight as well as the forces from components such as the guide rails, saddle, and tool holder. Fixed constraints are applied to the bottom two guide rail slots at the constrained part. After adding the constraints, the first six modal analyses of the beam were conducted. Through modal analysis, the modal frequencies and vibration modes of the beam can be obtained. The results of the first six modal frequencies are shown in Table 1.

Table 1. Modal Analysis of the First 6 Modes of the Original Beam

Order	Frequency/Hz
1	89.40
2	171.74
3	179.42
4	231.32
5	244.27
6	377.09

The low-order natural frequencies most effectively reflect the vibration characteristics of components such as the beam [9]. The first natural frequency of the original beam is 89.40 Hz, which is less than 100 Hz. Therefore, resonance may occur during machining, leading to potential failure. Moreover, the first natural frequency mode of the original beam exhibits a left-right rocking motion, making the beam prone to tilting, which could damage the beam and other related components of the machine tool.

4. Orthogonal Experimental Design for the Machine Tool Beam

4.1 Determine Experimental Factors and Optimization Design Objectives

In this study, the primary design objective during the optimization of the beam is to increase the natural frequency, with the first natural frequency being the main design target. In a multi-factor, single-objective design scenario, it is possible to clearly identify which factor achieves the best optimization effect for the optimization goal of the natural frequency. For the machine tool beam, factors such as the rib thickness, width, and arrangement layout are crucial to its performance [10]. Therefore, this study selects these factors for the orthogonal experimental design.

4.2 Orthogonal Experimental Design

Orthogonal experimental design is a highly efficient experimental method. It significantly reduces the number of experiments by selecting a subset of representative points from a comprehensive

experiment. For example, a full experiment with three factors and three levels requires 27 trials, while the orthogonal experimental design may only need 9 or 15 trials, thus greatly reducing the workload. It is characterized by being "orderly and comparable, with balanced dispersion" [11].

In this study, the final decision was to select rib thickness, rib width, number of partitions, and the distance between intermediate support rods as the factors for the orthogonal experiment. Based on the actual model dimensions, a 4-factor, 3-level orthogonal experimental design was arranged. The orthogonal experiment table is shown in Table 3. If a full experimental method were used for the four factors at three levels, 81 trials would be required. However, by adopting the L9(3⁴) orthogonal experiment, only 9 trials are necessary to analyze the data for each factor and its levels, thus obtaining the optimal combination of levels and greatly improving the experimental efficiency.

The following Table 2 shows the specific levels for each factor:

Table 2. Modal Analysis of the First 6 Modes of the Original Beam

Level/Factor	A: Number of Partitions (pieces)	B: Rib Thickness (mm)	C: Rib Width (mm)	D: Intermediate Support (mm)
1	5	25	25	590
2	7	35	35	690
3	9	45	45	790

Table 3. Orthogonal Design Table

Number	Factor: A	Factor: B	Factor: C	Factor: D
1	1	1	1	1
2	1	2	3	2
3	1	3	2	3
4	2	1	3	3
5	2	2	2	1
6	2	3	1	2
7	3	1	2	2
8	3	2	1	3
9	4	3	3	1

Table 4. Simulation Results of Each Mode

Number	First Order/Hz	Second Order/Hz	Third Order/Hz	Fourth Order/Hz	Fifth Order/Hz	Sixth Order/Hz
1	69.985	128.17	142.25	192.76	210.13	278.21
2	120.6	178.6	194.73	275.21	292.56	413.88
3	102.93	159.83	176.11	253.53	258.79	357.62
4	118.46	174.83	188.35	265.26	285.98	386.25
5	102.92	162.52	175.22	255.64	265.55	376.24
6	80.562	143.51	154.39	222.5	230.39	302.31
7	102.13	161.17	172.61	251.13	262.11	337.04
8	80.777	144.39	153.97	220.89	227.88	290.65
9	128.81	196.49	203.86	287.95	320.98	418.99
Original	89.404	171.74	179.52	231.32	244.27	377.09

4.3 Orthogonal Experimental Data Processing

Since low-order natural frequencies most effectively reflect the vibration characteristics of components such as the beam, and the first natural frequency of the machine tool beam has not reached 100 Hz, priority is given to the data processing of the first natural frequency for each model in this study.

4.3.1 Range Analysis

Range analysis is a simple statistical method primarily used to describe the dispersion of a dataset. Although the calculation of range analysis is relatively simple, it can provide the most direct and effective information in certain cases, making it one of the commonly used methods in orthogonal experiments. Table 5 shows the results of the range analysis.

Table 5. Range Analysis Results

Factor	Number of Partitions	Rib Thickness	Rib Width	Intermediate Support
Mean 1	97.838	86.858	77.108	100.572
Mean 2	100.647	101.432	122.623	101.097
Mean 3	103.906	104.101	102.660	100.722
Range	6.068	7.243	45.515	0.525

From the range analysis in the table, $R_3 > R_2 > R_1 > R_4$, meaning the four factors are ranked in terms of significance as follows: rib width, rib thickness, number of partitions, and intermediate span. Additionally, the main effects plot was obtained using Minitab, as shown in Figure 5:

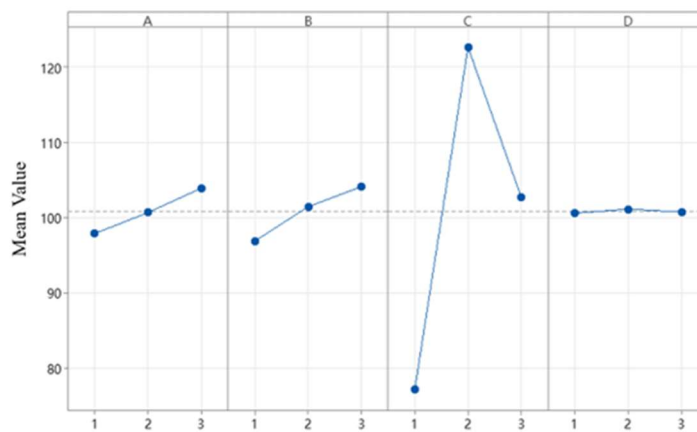


Figure 5. Main Effects Plot for Each Factor

4.3.2 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical method used to determine whether there is a significant difference between the means of two or more samples. By comparing the variance within the samples and between the samples, ANOVA can detect the relationship between variables. Table 6 shows the results of the variance analysis.

From Table 5, it can be seen that the analysis of variance (ANOVA) was used to study the differences in the experimental data with respect to the four factors. From the table above, we can observe that the samples of different factors A, B, and D (i.e., number of partitions, rib thickness, and intermediate span distance) do not show any significant difference for the experimental data ($p > 0.05$), meaning there is no notable difference.

Table 6. Orthogonal Design Table

Source	Degrees of Freedom	Adjc ss	Adj ms	F	P
A	2	55.32	27.66	0.05	0.950
B	2	80.49	40.25	0.08	0.928
C	2	3123.1	1561.54	68.76	0.000
D	2	0.44	0.22	0.00	1.000

Factor C (rib width) shows a significant difference at the 0.01 level ($F = 68.764, p = 0.000$), indicating a clear distinction. In summary, it can be concluded that samples for different factor C levels exhibit significant differences in the experimental data.

4.3.3 Determination of the Optimal Solution

Based on the above range analysis and variance analysis, the optimal solution can be obtained from the four factors that were set. The optimal combination is A3B3C2D2, which corresponds to 9 partitions, rib thickness of 45mm, rib width of 35mm, and intermediate span of 690mm. Since this combination does not exist in the orthogonal experiment, further simulation design is conducted for this model. Figure 6 shows the 3D model of the beam after optimization.

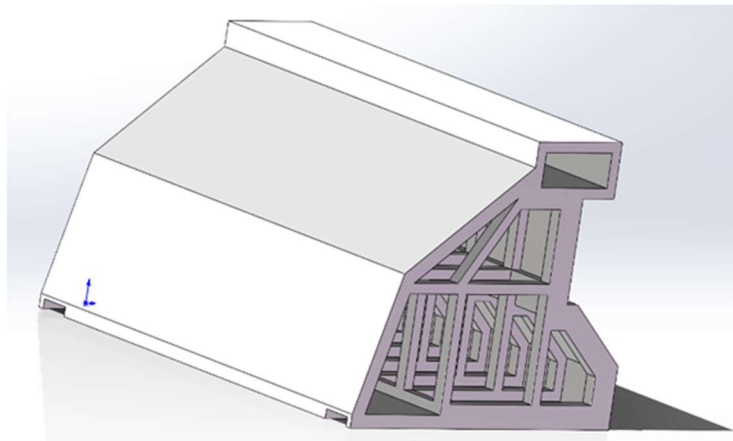


Figure 6. Optimized Beam Model

Table 7. Comparison of Optimization Results

Number	First Order/Hz	Second Order/Hz	Third Order/Hz	Fourth Order/Hz	Fifth Order/Hz	Sixth Order/Hz	Masskg
Before Optimization	89.404	171.74	179.42	231.32	244.27	377.09	1491.5
After Optimization	113.41	182.42	191.63	276.08	298.01	408.68	2566.95

When comparing the optimized model with the original model, the first-order frequency increased by 26.97%, and the frequencies of subsequent modes also showed improvements. However, the mass has increased. Therefore, considering the mass issue, further experiments will be conducted on the significant factors obtained from the variance analysis in Table 6. The goal is to achieve a balance between performance and mass.

5. Load Analysis and Design Parameters Determination

The lightweight design in this study was primarily derived from the orthogonal experiment and verified through the response surface experiment.

5.1 Orthogonal Experimental Design

In the optimized design scheme mentioned above, quality optimization was conducted. The analysis of the model revealed that the factors most influencing the beam's mass are rib thickness, outer wall thickness, and outer wall width. Combining the variance analysis results from Chapter 3, where factor C (rib width) was identified as a significant factor, it was decided to conduct another orthogonal experimental design for outer wall thickness and rib width to achieve structural optimization and lightweight design. The number of partitions and the span distance were selected from the optimized data in Chapter 3, which are 9 partitions and a span distance of 690mm, respectively. This experiment mainly compares the first-order frequency with the mass.

Table 8. Factors Level Table

Level/Factor	A: Outer Wall Thickness(mm)	B: Rib Thickness(mm)	C: Rib Width(mm)
1	30	20	20
2	40	30	30
3	50	40	40

Table 9. Orthogonal Design Table

Level/Factor	A: Outer Wall Thickness(mm)	B: Rib Thickness(mm)	C: Rib Width(mm)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 10. First-Order Frequency and Mass

Number	First Order/Hz	Mass/kg
1	71.67	1797.65
2	84.26	1938.95
3	95.50	2127.35
4	89.93	2049.35
5	102.19	2249.02
6	90.05	2139.91
7	106.07	2370.75
8	97.183	2307.90
9	107.88	2472.75
Original	89.404	1491.50
After Optimization	113.41	2566.95

Table 11. Range Analysis Results - First-Order Frequency

Factor	Outer Wall Thickness	Rib Thickness	Rib Width
Mean 1	83.81	89.22	86.30
Mean 2	94.06	94.54	94.02
Mean 3	103.71	97.81	101.25
Range	19.90	8.59	14.95

Table 12. Range Analysis Results - Mass

Factor	Outer Wall Thickness		Rib Width
Mean 1	1955	2073	2082
Mean 2	2146	2165	2164
Mean 3	2384	2247	2249
Range	429	174	167

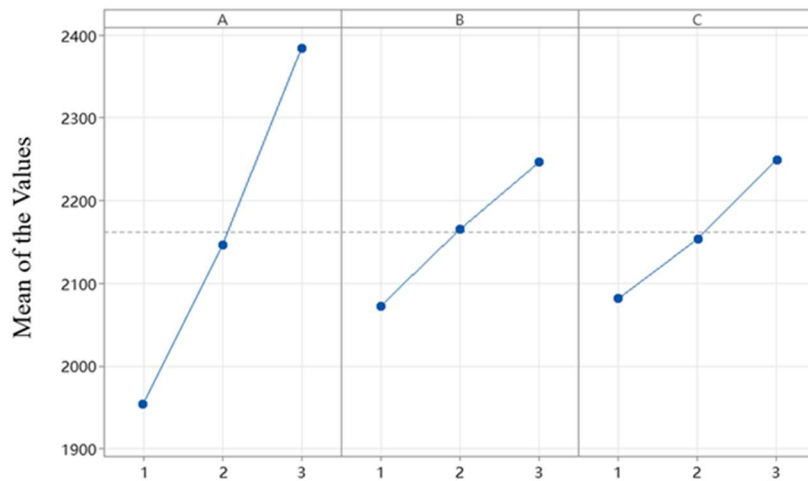


Figure 7. First-Order Frequency Main Effects Plot

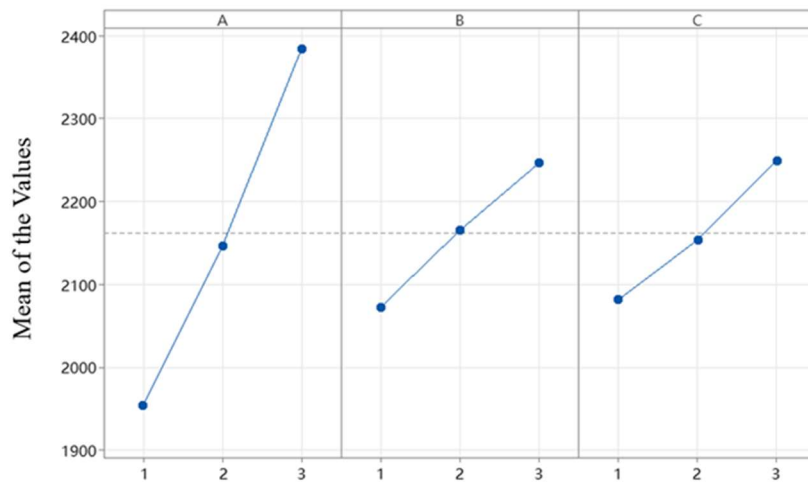


Figure 8. Main Effects Plot for Mass

From the range analysis in the table, for the first-order frequency, $R_1 > R_3 > R_2$, meaning the three factors are ranked in terms of significance as follows: outer wall thickness, rib width, and rib thickness. For mass, $R_1 > R_2 > R_3$, meaning the three factors are ranked in terms of significance as follows: outer wall thickness, rib thickness, and rib width.

In combination with the main effects plot, it can be concluded that Factor A, which is outer wall thickness, has the greatest impact on both mass and the first-order frequency.

5.2 Response Surface Experiment

The main purpose of a response surface experiment is to optimize the influencing factors by establishing a relationship between the response variable (output variable) and one or more independent variables (factors), using as few experiments as possible. It is widely applied in industrial process optimization, product development, and quality improvement, especially when seeking the best combination of conditions that affect a specific response. The core idea is to design a reasonable number of experiments to precisely study the relationship between each factor and the response value, allowing for the rapid and effective determination of the optimal conditions in a multi-factor system.

5.2.1 Response Surface Experiment Regression Model and Variance Analysis

In this study, Design-Expert V13 software was used to process and analyze the data, resulting in the first-order natural frequency response surface experiment regression model:

$$Y = -6.103 + 1.997A + 0.6113B + 1.081C - 0.002AB - 0.009AC + 0.010BC - 0.009A^2 - 0.007B^2 - 0.004C^2$$

Table 13. Range Analysis Results - First-Order Frequency

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	P	Significance
Regression Model	1331.47	9	147.94	3193.76	< 0.0001	2082
A-Outer Wall Thickness	715.27	1	715.27	15441.29	< 0.0001	2164
B-Rib Thickness	139.72	1	139.72	3016.29	< 0.0001	
C - Rib Width	462.14	1	462.14	9976.71	< 0.0001	
AB	0.1673	1	0.1673	3.61	0.0992	
AC	3.23	1	3.23	69.83	< 0.0001	
BC	4.05	1	4.05	87.52	< 0.0001	
A ²	3.41	1	3.41	73.63	< 0.0001	
B ²	2.00	1	2.00	43.21	0.0003	
C ²	0.8142	1	0.8142	17.58	0.0041	
Residual	0.3243	7	0.0463			
Lack of Fit	0.3243	3	0.1081			
Pure Error	0.0000	4	0.0000			
Total	1331.80	16				
Deviation						

The regression equation coefficient significance test shows that the linear terms A and C are highly significant, and B is significant. Based on the F-values of the three main factors, the impact on the first-order frequency of the machine tool beam follows the order: $A > C > B$, that is, outer wall thickness > rib width > rib thickness.

5.2.2 Response Surface Analysis of the Effect of Each Interaction on the First-Order Frequency

Work also can be done by finite element analysis software and integrated into the optimization design software platform. The Pareto Frontier can be obtained through the platform. The load direction is oriented at a 45° angle to the upper left, aligning with the direction of the optimal frequency as determined in Figure 13. The resulting curve is shown in Figure 14, where the points in the Pareto Frontier are classified by volume fraction.

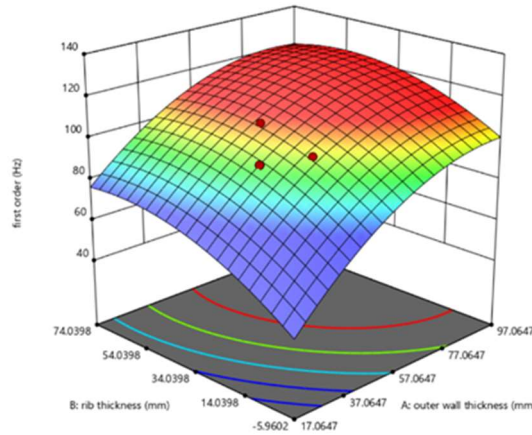


Figure 9. Interaction between Factors A and B

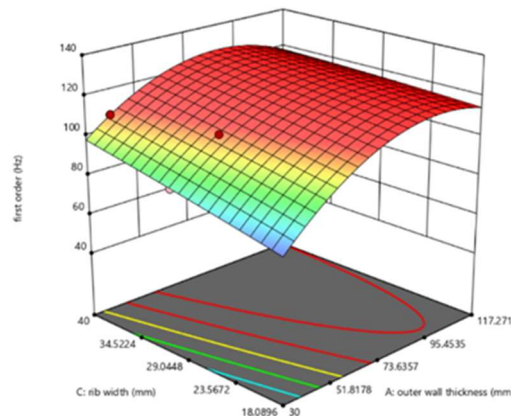


Figure 10. Interaction between Factors A and C

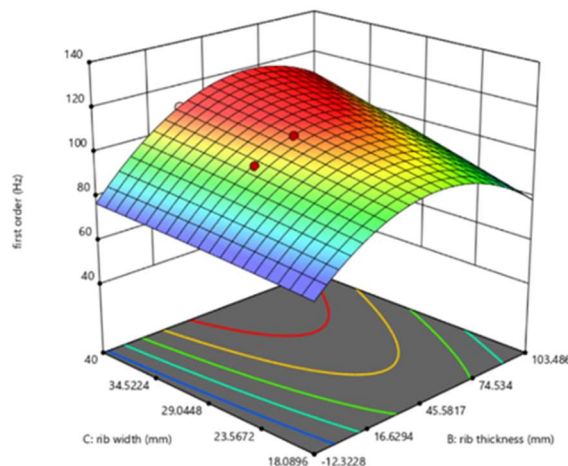


Figure 11. Interaction between Factors B and C

As shown in Figures 9, 10, and 11, the response surface graphs illustrate the relationship between the first-order natural frequency of the bed and its outer wall thickness, rib thickness, and rib width. These results verify that the optimal performance of the machine tool beam occurs when the outer wall thickness is 48mm, the rib thickness is 36mm, and the rib width is 37mm.

5.3 Final Solution Determination

Considering both the orthogonal experiment and the response surface experiment, the response surface experiment provides more accurate values for each factor, allowing the minimum mass to be achieved while ensuring the first-order frequency. Therefore, the optimal solution obtained from the response surface experiment is chosen as the final solution. The final solution is selected as an outer wall thickness of 48mm, rib thickness of 36mm, and rib width of 37mm. Finite element analysis was performed on this configuration, and Figure 12 shows its 3D model, while Figure 13 shows its first-order mode.

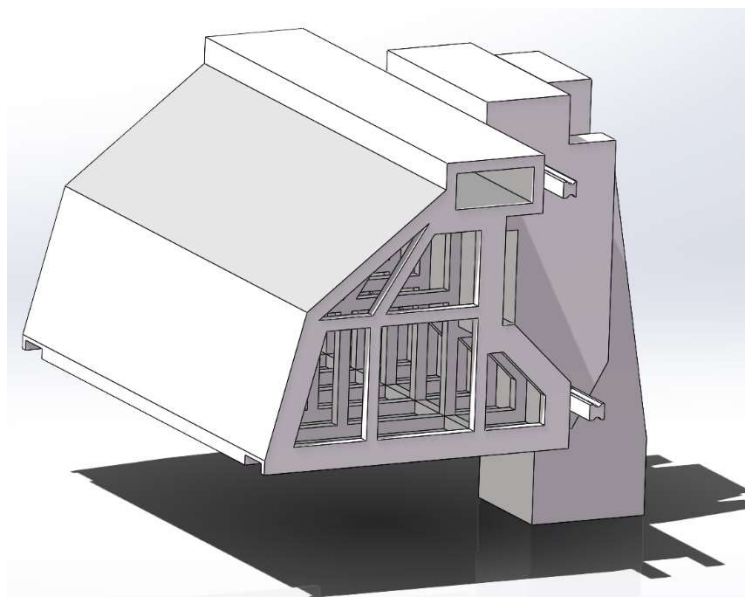


Figure 12. 3D Model

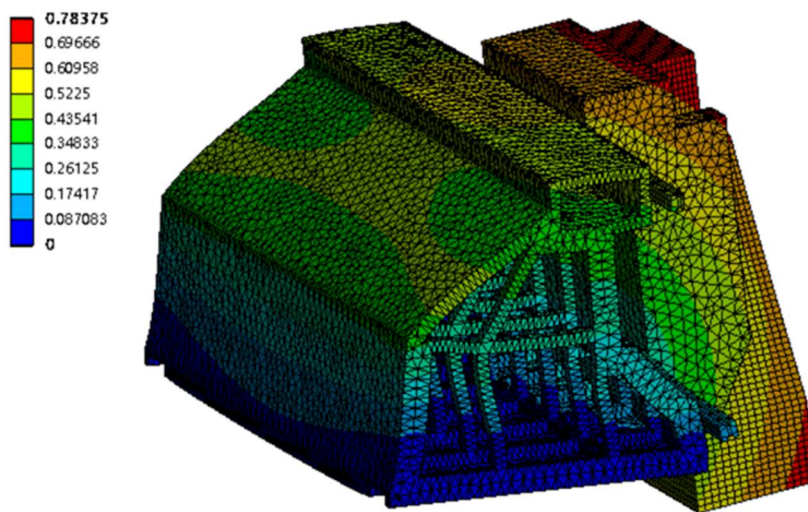


Figure 13. First-Order Mode

Table 14. Comparison of Optimization Results

Serial No.	First Order/Hz	Mass/kg
Before Optimization	113.41	2566.95
After Optimization	110.17	2472.75

Comparing the results, the frequency only decreased by 0.28% after the second optimization, while the mass was reduced by 3.6%. The overall performance of the beam improved significantly after optimization.

6. Conclusion

This paper utilizes advanced 3D modeling software SolidWorks and finite element analysis software Ansys to accurately construct models and perform modal analysis of the machine tool beam and the saddle tool holder. Based on this, an optimization strategy for the machine tool beam based on the principles of orthogonal experimental design is proposed. This method comprehensively considers four key factors in the beam design, including rib thickness, rib width, number of partitions, and intermediate span distance. By constructing a four-factor, three-level orthogonal experimental design and using the first-order natural frequency of the beam as the core evaluation index, the multi-factor collaborative optimization of the beam structure is achieved, effectively overcoming the limitations of traditional design methods that consider only one factor at a time.

Furthermore, after completing the orthogonal experimental design, to pursue economic efficiency and sustainability in the beam design, this paper introduces the response surface method and successfully constructs a response surface regression model. In the lightweight design process, special emphasis is placed on reducing the mass while ensuring both the dynamic and static performance of the beam. Using this method, this paper not only validates the effectiveness of the orthogonal experimental design but also significantly reduces the mass of the beam, achieving a balanced optimization of both mass and performance, providing new theoretical support and practical guidance for machine tool beam design.

(1) In this paper, an orthogonal experimental method is used for the multi-objective optimization design of the beam. By reducing the number of simulation trials, the optimal parameter combination is analyzed from the experimental data using range analysis and variance analysis, improving the efficiency of the optimization design. This demonstrates the strong engineering applicability of orthogonal experiments. The method expands the application field of orthogonal experiments and provides valuable theoretical foundations and methodological references for the optimization design of other machine tool components.

(2) One of the main objectives of structural lightweight design is to achieve the maximum improvement in structural dynamic and static performance under the same mass condition. In this paper, the optimal combination is obtained through response surface experiments and orthogonal experiments, which is “outer wall thickness 48mm-rib thickness 36mm-rib width 37mm-9 partitions-intermediate support distance 690mm.” The first-order frequency is 110.17 Hz, meeting the performance requirements of the machine tool beam. Compared to the results obtained from the orthogonal experiment alone, the mass is reduced by 3.6%.

(3) In future experimental designs, the range of experimental factors can be expanded to include factors such as the shape of the rib plates and beam width. Combining methods such as sensitivity analysis can further optimize the structural performance of the machine tool beam, leading to even more optimized design solutions.

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