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Crossbeam Structure Optimization Using Orthogonal Experimental Combined Weighting Method

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Abstract: The machining quality of the gantry machining center is directly impacted by the structural performance of the crossbeam, which is one of its key moving components. The optimization of the overall performance of the crossbeam is aimed to be achieved through the conduct of finite element analysis and the utilization of orthogonal experimental methods, along with a combination weighting approach to strengthen the quantitative data analysis. The research investigates the influence of different design approaches on the rigidity and vibration characteristics of the crossbeam. By integrating structural optimization and data analysis, a well-rounded crossbeam design solution with superior overall performance is proposed. Following optimization, the beam's mass was reduced by 205.6kg, a decrease of 9.4%, maximum deformation reduced by 0.0143mm, a decrease of 50%, maximum equivalent stress decreased by 0.839MPa, a decrease of 7.4%, and simultaneously, the first-order natural frequency increased by 7.541Hz, a rise of 26.29%. Through effective optimization, the crossbeam's static and dynamic performance improved while achieving lightweight design under the premise of ensuring rigidity.

Keywords: Crossbeam; orthogonal experimental design; combined weighting method; sensitivity analysis; lightweight design; optimization design.

1. Introduction

As the "mother machine" of industry, the technological level of CNC machine tools directly determines the advancement of manufacturing processes. At present, China's machine tool industry is undergoing a critical phase of transformation and upgrading, where domestic machine tools must overcome technical bottlenecks such as high speed, high efficiency, and high precision[1]. Machine tools, as essential manufacturing equipment, require upgrading and innovation. The primary task in improving the machining accuracy of machine tools is optimizing the beam design[2]. In gantry machining centers with movable beams, the beam's capability to ascend and descend offers a larger machining range and stronger cutting ability, making it particularly suitable for the high-precision, high-efficiency machining of large components such as diesel engine casings, generator housings, and overall battery trays for new energy vehicles. The rationality of the beam structure directly affects the manufacturing cost and overall performance of the gantry machine tool, as it serves as a critical support component of the machining center[3].

In recent years, numerous methods have been proposed by scholars both domestically and abroad for optimizing beam structures. Zhong H. L.[4] and others introduced a support-free design method, opening new avenues for lightweight beam designs. Sun Q.[5] and colleagues applied topology optimization to welded beams, resulting in a 10% reduction in weight, with overall performance improvements in welded beams. Bai Hongliang[6] and his team, through modifications to the beam structure, achieved weight reduction and increased rigidity. Guo Linna[7] and her team enhanced the beam's operational efficiency by optimizing the stiffener layout, reducing deformation by 20.265% and increasing the first natural frequency by 4.405%. Jiang Shufeng[8] and others used a combination of the Analytic Hierarchy Process (AHP) and the grey relational analysis method to investigate the relationship between the number of stiffeners, stiffener thickness, and the static and dynamic characteristics of the beam. Based on their analysis, they performed a secondary design to arrive at the optimal beam structure. These studies provide insights and approaches for beam structure design and optimization, with the investigation of beam stiffener types being a particularly active area of research.

In this paper, the beam of a CNC gantry machining center with a movable beam is taken as the research object. First, SolidWorks software is used to create a three-dimensional model of the beam, and ANSYS software is used to conduct finite element static analysis. As the static and dynamic performance of the beam is influenced by multiple factors, orthogonal experiments and fuzzy comprehensive evaluation methods are employed to optimize the design scheme. Subsequently, sensitivity analysis and optimization of key dimensions in the beam structure are conducted to determine the final beam design dimensions.

2. Orthogonal Experiment Design and Finite Element Analysis of the Crossbeam

2.1. Orthogonal Experiment Design for the Beam Structure

2.1.1. Design Factors, Levels, and Evaluation Criteria

In this study, the structural design of the machine tool beam is carried out by combining traditional beam design concepts with modern engineering design features, considering the following four factors:

(1) Overall structural layout of the crossbeam**:** The structural layout of the beam determines the manner in which loads are applied to it. Two main forms are considered, as shown in Figure 1. One design features a rectangular cross-section in the middle of the beam, while the other features a trapezoidal cross-section in the middle. Both structures are symmetrical, allowing the slide assembly to move along the beam.

(2) Rail layout**:** As shown in Figure 1, the rail types for the

beam mainly include hard rails and linear rails. Hard rails can withstand greater operational loads, making the movement of components more stable. In contrast, linear rails allow for faster machine operation speeds, leading to higher machining precision.

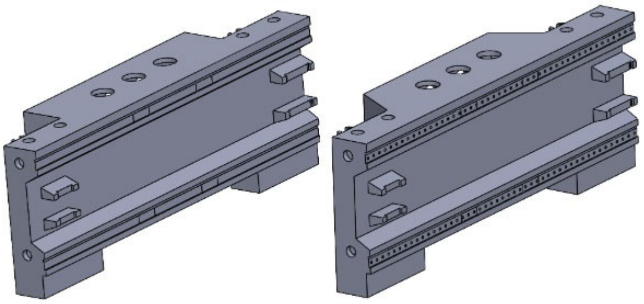
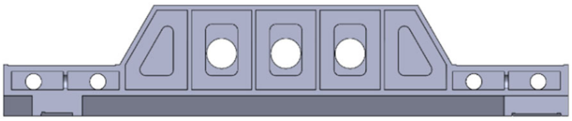
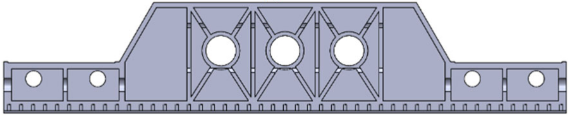

(A) Rectangular hard rail (B) Trapezoidal linear rail

Figure 1. Layout and rail arrangement of the crossbeam structure

(3) Stiffener structure type and thickness**:** To enhance the static and dynamic performance of the beam and achieve a lightweight design, the selection of stiffener structure type and thickness is crucial. The type and thickness directly affect the beam's overall mass. Two thicknesses, 20 mm and 25 mm, have been preliminarily determined. Additionally, four types of stiffener structures—Type A, Type B, Type C, and Type D—have been designed, as shown in Figure 2.


Type A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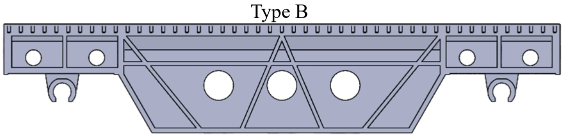
Type C

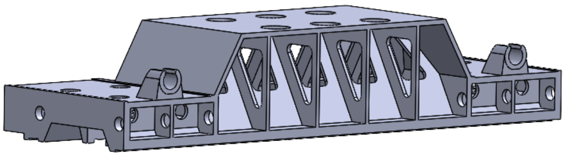
Type D

Figure 2. Crossbeam ribbed plate structure

To better determine the structural design and optimization plan for the beam, a comprehensive and accurate evaluation of different beam structures under various factor levels is required. Considering lightweight design, static performance, and vibration resistance, the evaluation criteria are set as mass, maximum deformation, maximum equivalent stress, and first natural frequency.

2.1.2. Orthogonal Experimental Design

Orthogonal experimental design, also known as Orthogonal design, is a method used for optimal design when there are numerous factors and levels involved[9]. It is a highly scientific experimental design method that selects representative points from a comprehensive set of experiments for testing. By employing orthogonal experiments, representative factors can be chosen as level parameters for the beam structure design, thus reducing the workload in the early stages of beam optimization. Therefore, an orthogonal table was designed, as shown in Table 1. Based on the determined factor levels, an orthogonal experimental plan for the structural design and optimization of the beam was established, as detailed in Table 2.

Table 1. Crossbeam structural design factor level table

Level	Factor			
	ribbed slab structure	ribbed slab thickness/mm	beam structure layout	guide rail layout
1	Type A	20	rectangular section	guideway
2	Type B	25	trapezoidal section	solid rail
3	Type C			
4	Type D			

Table 2. Orthogonal experimental design table for crossbeam structure

Plan	Factor level			
	ribbed slab structure	ribbed slab thickness /mm	beam structure layout	guide rail layout
1	Type A	20	rectangular section	guideway
2	Type A	25	trapezoidal section	solid rail
3	Type B	20	rectangular section	solid rail
4	Type B	25	trapezoidal section	guideway
5	Type C	20	trapezoidal section	guideway
6	Type C	25	rectangular section	solid rail
7	Type D	20	rectangular section	solid rail
8	Type D	25	trapezoidal section	guideway

2.2. Finite Element Structural Analysis of the Beam

2.2.1. Establishment of the Finite Element Model for the Beam

The three-dimensional model of the beam structure was created using SolidWorks software. The model was then imported into the static structural module in Ansys Workbench for finite element static analysis. Due to the complexity of the forces acting on the beam and its irregular structure, some small details are not conducive to mesh generation, and their influence on the static analysis results is minimal. To further improve the accuracy of the analysis results and simplify the computational load, non-essential small features, such as minor sand holes, small chamfers, and fillets, were excluded during the modeling process.

During the finite element analysis, the relevant material properties and parameters of the beam were set. Gray cast iron HT300 was used as the material, with its main properties input as follows: elastic modulus of 130 GPa, Poisson's ratio of 0.3, and density of 7300 kg/m³. In the pre-processing stage, mesh generation was performed using the default Ansys meshing method, with adjustments made to the element size as needed. The beam's load was applied according to the extreme working conditions of the beam, where the saddle and ram are positioned at the midpoint along the beam's length[10]. The ram was set to be fully extended, and the finite element model of the original beam, as shown in the figure below, was obtained.

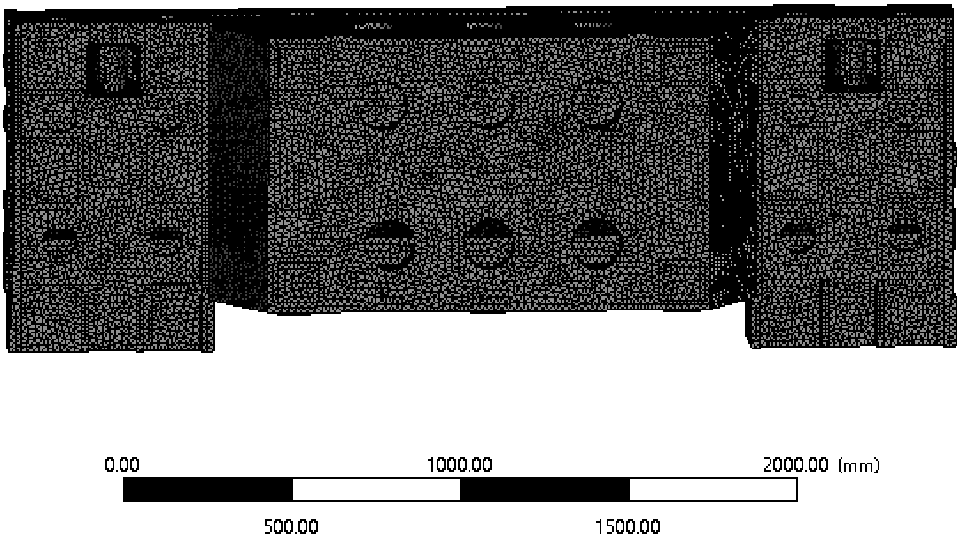

Figure 3. Finite element analysis model of the original crossbeam

After the meshing of the original beam was completed, a total of 591,357 nodes and 357,106 elements were generated.

The addition of loads is a critical step in finite element static analysis[11]. Since the beam only moves in the vertical direction during operation and its deformation is minimal, the torque caused by the cutting force is also minimal. Therefore, fixed constraints were applied at the vertical connection points, and the torque produced by the cutting force was applied as a remote force. When setting the load parameters on the beam, the load from the weight of the ram, which is approximately 4000 N, was applied to the rail connection surface of the beam. The cutting reaction forces during operation were calculated as $F_x = 3249.6$ N, $F_y = 1200$ N, and $F_z = 2000$ N. As the self-weight of the beam cannot be neglected, standard gravitational acceleration in the vertical direction was also considered.

2.2.2. Beam Simulation Results

Based on the orthogonal experiment design table, different structural schemes for the beam were obtained. Then, corresponding finite element models were created for each scheme, and static and dynamic analyses were performed. Ultimately, the deformation, maximum equivalent stress, and the first six natural frequencies of the machine tool beam were obtained through finite element analysis. The results are shown in the table below:

Table 3. Static simulation analysis results of the crossbeam

Plan	Factor				Evaluation criteria			
	ribbed slab structure	ribbed slab thickness /mm	beam structure layout	guide rail layout	Mass/kg	Maximum deformation /μm	Maximum equivalent stress //MPa	First-order natural frequency /Hz
1	Type A	20	trapezoidal	guideway	2098	26.486	13.0052	35.88
2	Type A	25	rectangular	solid rail	2212	24.848	12.9311	33.81
3	Type B	20	trapezoidal	solid rail	2284	28.771	14.9416	33.16
4	Type B	25	rectangular	guideway	2615	17.931	12.9447	32.49
5	Type C	20	trapezoidal	guideway	2152	30.169	13.5858	35.43
6	Type C	25	rectangular	solid rail	2373	23.129	12.5665	34.13
7	Type D	20	trapezoidal	solid rail	2177	25.675	12.5102	35.47
8	Type D	25	rectangular	guideway	2306	20.994	12.1867	34.63

3. Selection of the Beam Structure Optimization Scheme

Due to the large amount of data in Table 3, it is difficult to determine the advantages and disadvantages of the proposed schemes through simple analysis[12]. To select the optimal beam structure design, the fuzzy comprehensive evaluation method was used to analyze and process the data in Table 3.

3.1. Determination of Evaluation Index Weights

The weight of evaluation criteria is crucial in fuzzy comprehensive evaluation, as its accuracy directly impacts the reliability of the results. Traditional fuzzy comprehensive evaluation methods typically use subjective weighting methods, but these are prone to personal bias, potentially leading to significant deviations in the results[13-14]. To make the orthogonal experiment results more objective and reduce the influence of data errors on the beam analysis, this study adopts a combination weighting method, integrating the entropy weight method and fuzzy analytic hierarchy process (FAHP), to calculate the evaluation index weights. This approach ensures more objective results from the orthogonal experiment.

3.1.1. Calculation of Weights Using the Entropy Method

The entropy weight method (EWM) is a multi-criteria decision-making technique used to determine the weight of each criterion in the decision-making process. The relative importance of criteria is assessed by calculating their entropy values and weights.

According to the literature[12], suppose there are "n" design schemes in the beam orthogonal experimental design, represented as set "S". The evaluation criteria set is denoted as "U", where "a_{ij}" represents the simulation data of the "j"th criterion for the "i"th design scheme. Based on the description and the data in Table 3, an evaluation criteria matrix A = (a_{ij})n×m is established.

Since the units of the evaluation criteria differ, making them incomparable, all criteria in matrix *A* need to be dimensionless before further analysis.

$$a_{ij}^{'} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{1}$$

The weights of the evaluation criteria calculated using the entropy method are represented as *W*, where *W* = [w_1, w_2, ..., w_m].:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)} \tag{2}$$

Where, $e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} a'_{ij} \ln a'_{ij}$,*j*=1, 2, ⋯*m*.

3.1.2. Calculation of Weights Using the Fuzzy Analytic Hierarchy Process

The fuzzy analytic hierarchy process (FAHP) is applied to compare the priority relationships among evaluation criteria using the 0.1~0.9 scale method[15]. A weight judgment matrix B = (bhj)m×n is then established to evaluate the importance of the criteria. The weights of the judgment matrix B are calculated based on the formula derived in the literature[16]. $W'=[w'_1, w'_2, \cdots, w'_m]$, where:

$$w'_h = \frac{\sum_{j=1}^{m} b_{hj} + \frac{m}{2} - 1}{m(m-1)} \tag{3}$$

Where, $\sum_{j=1}^{m} w'_h = 1, w'_h \geq 0$, (*j*=1, 2, ⋯, *m*)

Next, the consistency of the judgment matrix *B* needs to be tested to determine whether the weights obtained through formula (3) are reasonable[17]. Since the evaluation involves a high degree of subjectivity and partial understanding of the evaluation system, the previously established judgment matrix may not be entirely accurate. Therefore, consistency testing is required to ensure the accuracy of the judgment matrix. Where:

$$w'_{hj} = \frac{w'_h}{w'_h + w'_j}, \; h, j=1, 2, \cdots, m \tag{4}$$

Let $S=(w'_{hj})_{m\times m}$ be the eigenmatrix of the judgment matrix *B*.

The consistency index between matrix *B* and matrix *S* is calculated as follows.

$$I(B,\mathrm{S})=\frac{1}{m^2}\sum_{h=1}^{m}\sum_{j=1}^{m}\left|b_{hj}+w'_{hj}-1\right| \tag{5}$$

The decision-maker evaluates the consistency of the judgment matrix based on the relationship between the consistency index *I*(B, S) and the tolerance level *α*. When I(B, S) ≤ α (typically *α* = 0.2), the judgment matrix is considered to have satisfactory consistency.

In practical problems, comparison judgment matrices are usually provided by multiple experts. Suppose there are t experts, then the judgment matrix is denoted as $B_k=(b^k_{hj})_{m\times m}$, $k=1, 2, \cdots, t$. The corresponding set of weight vectors is represented as $W'_k=[W'_1,\ W'_2,\cdots,W'_t]$, and the corresponding eigenmatrix is denoted as $S_k=(w'^k_{hj})_{m\times m}$. If the judgment matrix Bk and the consistency between the matrices are satisfactorily achieved, the fuzzy analytic hierarchy process weight expression is given by:

$$W^{\bullet}=[w^{\bullet}_1,\ w^{\bullet}_2,\cdots,\ w^{\bullet}_m]=\frac{1}{t}\sum_{k=1}^{t}w'_k \tag{6}$$

3.1.3. Calculation of Combined Weights

The subjective and objective weights determined by the fuzzy analytic hierarchy process and the entropy method are combined using a multiplicative synthesis normalization method[18]. The resulting weights for the fuzzy comprehensive evaluation method are shown as follows.

$$P=[p_1,\ p_2,\cdots,\ p_m] \tag{7}$$

Where: $p_j=\dfrac{w_j w^{\bullet}_j}{\sum_{j=1}^{m} w_j w^{\bullet}_j}$, $j=1,\ 2,\ \cdots,\ m$.

3.2. Determination of the Fuzzy Comprehensive Evaluation Model

When calculating the fuzzy relationship matrix, each beam design scheme is evaluated using a single evaluation criterion. The rating of the design scheme for each evaluation criterion is denoted as r_j, as shown below.

$$r_j=[r_{1j},\ r_{2j},\cdots,\ r_{nj}]^T \tag{8}$$

Where, r_j represents the fuzzy subset of the evaluation criteria., $j=1, 2, 3, \cdots, m$.

There are mainly two types of evaluation criteria, as shown in equation (9). For example, a higher first natural frequency is preferable, while smaller values for mass, maximum deformation, and maximum equivalent stress are more desirable. Therefore, these two types of criteria need to be considered separately.

$$r_j=\begin{cases}\dfrac{a_j-\min a_j}{\max a_j-\min a_j}, & \text{the larger the better indicator}\\[2ex] \dfrac{\max a_j-a_j}{\max a_j-\min a_j}, & \text{the smaller the better indicator}\end{cases} \tag{9}$$

In formula (9), a_j represents the simulation data for the n beam design schemes corresponding to the j-th evaluation indicator. The n beam structure design schemes are evaluated for the m evaluation indicators, and the corresponding single-indicator evaluation matrices are obtained. These matrices are then combined to form a fuzzy relation matrix, expressed as follows:

$$R=\begin{pmatrix} r_{11} & \cdots & r_{1m}\\ \vdots & \ddots & \vdots\\ r_{n1} & \cdots & r_{nm}\end{pmatrix} \tag{10}$$

By applying the weighted average algorithm [19] to perform the corresponding matrix operations on the fuzzy matrix, the fuzzy comprehensive evaluation matrix was obtained as follows.

$$C=P\bullet R=[c_1,\ c_2,\cdots,\ c_n] \tag{11}$$

Where, $c_i=\sum_{j=1}^{m}p_i r_{ij}$, $i=1,\ 2,\ \cdots,\ n,\ j=1,\ 2,\ \cdots,\ m$.

The superiority of beam design schemes is evaluated by comparing the magnitudes of c_i, and thereby determining the optimal beam design scheme.

3.3. Optimal Parameter Combination

Based on the simulation data from Table 3 in Chapter 1 and the calculations using formulas (1) and (2), the weights obtained using the entropy method are shown as follows.

$$W=[0.201\quad 0.200\quad 0.197\quad 0.201\quad 0.202]$$

In modern design engineering, it is common for multiple industry-related experts to collaboratively participate in large decision-making processes. In this beam design, two experts were invited to evaluate each indicator using the 0.1 to 0.9 scale method, resulting in the fuzzy judgment matrix presented in the table below.

Table 4. Fuzzy judgment matrix of evaluation indicators

Objective		U_1	U_2	U_3	U_4
Expert 1	U_1	0.5	0.6	0.7	0.7
	U_2	0.4	0.5	0.6	0.6
	U_3	0.3	0.4	0.5	0.5
	U_4	0.3	0.4	0.5	0.5
Expert 1	U_1	0.5	0.6	0.6	0.7
	U_2	0.4	0.5	0.6	0.6
	U_3	0.4	0.4	0.5	0.6
	U_4	0.3	0.4	0.4	0.5

According to formula (3), the weights of the evaluation indicators from the two experts are calculated as shown below:

$$W'_1=[0.225\quad 0.200\quad 0.175\quad 0.175]$$

$$W'_2=[0.225\quad 0.205\quad 0.185\quad 0.170]$$

By employing formula (4), the characteristic matrix of the fuzzy judgment matrix is obtained as follows:

$$S_1=\begin{pmatrix}0.500 & 0.529 & 0.563 & 0.563\\ 0.471 & 0.500 & 0.533 & 0.533\\ 0.437 & 0.467 & 0.500 & 0.500\\ 0.437 & 0.467 & 0.500 & 0.500\end{pmatrix}$$

$$S_2=\begin{pmatrix}0.500 & 0.523 & 0.549 & 0.570\\ 0.477 & 0.500 & 0.526 & 0.547\\ 0.451 & 0.474 & 0.500 & 0.521\\ 0.430 & 0.453 & 0.479 & 0.500\end{pmatrix}$$

Using formula (5) to perform calculations, the consistency indices of the judgment matrix (B) and the characteristic matrix (S) are obtained as follows.:

$$I（B_1, S_1） =0.126$$

$$I（B_2, S_2） =0.133$$

The calculation results show that both consistency indices are less than 0.2. Therefore, it can be concluded that both judgment matrices satisfy the criteria for acceptable consistency, indicating that the weights of the evaluation indicators are reasonable.

Additionally, the satisfactory consistency of the judgment matrices B_1 and B_2 is confirmed by: $I(B_1, B_2) = 0.175$, which is also less than 0.2, thus meeting the criteria for acceptable consistency.

The fuzzy hierarchical weights are obtained as shown below according to formula (6):

$$W^{\bullet}=[0.225 \quad 0.202 \quad 0.180 \quad 0.173]$$

The combined weights of the fuzzy comprehensive method are obtained as shown below according to formula (7):

$$P=[0.226 \quad 0.199 \quad 0.181 \quad 0.174]$$

According to formulas (8), (9), and (10), the fuzzy relation matrix is calculated as follows:

$$R=\begin{pmatrix}1.000 & 0.301 & 0.703 & 1.000\\ 0.779 & 0.435 & 0.730 & 0.611\\ 0.640 & 0.114 & 0.000 & 0.198\\ 0.000 & 1.000 & 0.725 & 0.000\\ 0.896 & 0.000 & 0.493 & 0.867\\ 0.468 & 0.575 & 0.862 & 0.484\\ 0.847 & 0.367 & 0.883 & 0.879\\ 0.598 & 0.750 & 1.000 & 0.631\end{pmatrix}^T$$

The comprehensive evaluation matrix for the machine tool beam structure design is obtained from formula (11):

$$C=[0.807\ 0.690\ 0.359\ 0.330\ 0.663\ 0.553\ 0.766\ 0.701]$$

From the calculation results, it is known that Scheme 1 scores the highest in the beam structure design.

A comparison with other schemes using Table 3 reveals that Scheme 1 ranks first in the evaluation indicators of mass and first-order natural frequency; however, it ranks sixth in maximum deformation and maximum equivalent stress indicators. Thus, it is evident that although the improved comprehensive fuzzy evaluation method can select the optimally comprehensive scheme, greatly enhancing the objectivity and reliability of the evaluation, this method only determines the best comprehensive scheme among all, not the best in all indicators. Therefore, there is still room for further optimization in the design.

4. Optimization of the Preferred Beam Structure Scheme

Through the orthogonal design experiments and the fuzzy comprehensive evaluation method used in the previous chapter, the structural scheme of the machine tool beam has been optimally selected, preparing the groundwork for further optimization.

Due to the relatively weak static performance of Scheme 1's beam, the dimensional parameters that significantly affect the maximum deformation, maximum equivalent stress, and first-order natural frequency have been identified. Additionally, the influence of the beam's own weight on deformation cannot be overlooked, hence the mass of the beam needs to be minimized as much as possible.

4.1. Dimensional Sensitivity Analysis

Based on the structural characteristics of the optimized beam scheme, the following nine key dimensions have been selected as input parameters for the sensitivity analysis: thickness of the middle rib plate P_1, spacing between rib plates P_2, distance of the rib plate from the inner wall P_3, spacing between openings P_4, distance from the openings to the upper wall P_5, side distance of the left and right openings P_6, upper wall thickness P_7, thickness of the left and right walls P_8, and thickness of the lower wall P_9, as shown in the figure below.

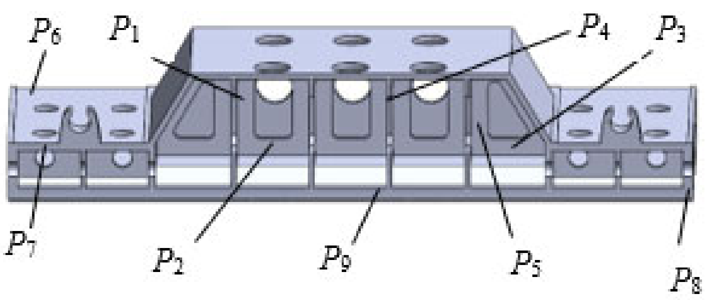

Figure 4. Selection of key dimensions for machine tool crossbeam

After parameterizing the aforementioned nine dimensions, three output parameters were selected: mass of the beam, maximum deformation, and first-order natural frequency, to establish a multi-objective function relationship with the nine dimensions. Due to the large number of input parameters, 100 sample points were set, with the value range automatically set by the parameter correlation module. Subsequently, the parameter correlation module in Ansys Workbench was used to perform the dimensional sensitivity analysis, resulting in the sensitivity of the input parameters to the output parameters as shown in the figure below:

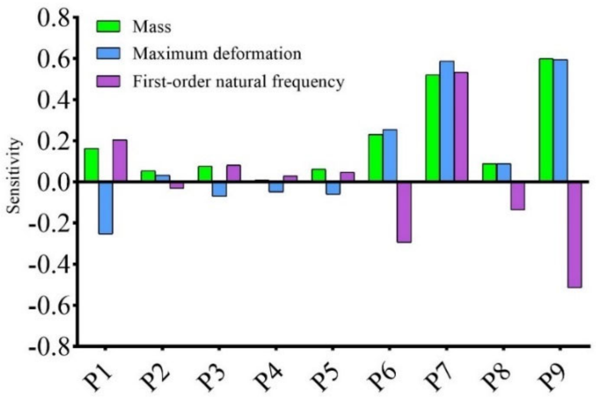

Figure 5. Sensitivity analysis of key dimensions for the crossbeam

From the figure above, it can be seen that the sensitivity values are both positive and negative. When the sensitivity is positive, it indicates that as the input parameters increase, the output parameters also increase; when the sensitivity is negative, it indicates that as the input parameters increase, the output parameters decrease. The sign of the sensitivity does not denote its magnitude but indicates a positive or negative correlation, while the magnitude of sensitivity refers to the size of its absolute value [20-21].

Through the sensitivity analysis of the key design dimensions of the beam, it was found that the parameters P2, P3, P6, P7, P9, and P14 have a smaller impact on the output parameters compared to other parameters, and hence are negligible in subsequent optimizations; therefore, the parameters P1, P6, P7, and P9, which are highly sensitive to the optimization objectives, were selected for optimization design.

Based on the results of the beam structural design dimension sensitivity analysis and the beam structural design data, after generating design dimensions in the response surface optimization within Ansys Workbench, modifications were made to the range of dimensions to a certain extent, resulting in the following table showing the range of dimensions for the optimized beam structure：

Table 4. Range of values for the crossbeam dimensions to be optimized

Parameter	Initial value (mm)	Range of values (mm)
P_1	20	18~22
P_8	110	100~120
P_{13}	35	30~40
P_{15}	60	55~65

4.2. Dimensional Optimization Results Analysis

Based on the previously determined dimensions and their ranges for the beam awaiting optimization, the importance levels of 'mass', 'maximum deformation', and 'first-order natural frequency' were set to default during the optimization process. Subsequently, constraints were set for each optimization objective to ensure that the results after optimization would not be lower than before. Given that the optimized dimensions were computed and fitted using ANSYS Workbench software, and that achieving these precise dimensions in actual production is challenging[20], it was necessary to round off the optimized dimensions. The performance of the beam structure after this rounding was reanalyzed. The results are shown in the following table.

Table 5. Rounded results of crossbeam design dimensions

Parameters	Optimized values (mm)	Rounded dimensions (mm)
P_1	18.1	18
P_8	100.5	100
P_{13}	30.25	30
P_{15}	55.25	55

Based on the rounded results from Table 5, the three-dimensional model of the beam was modified, and the corresponding finite element static analysis was conducted. The analysis results are shown in the figure below：

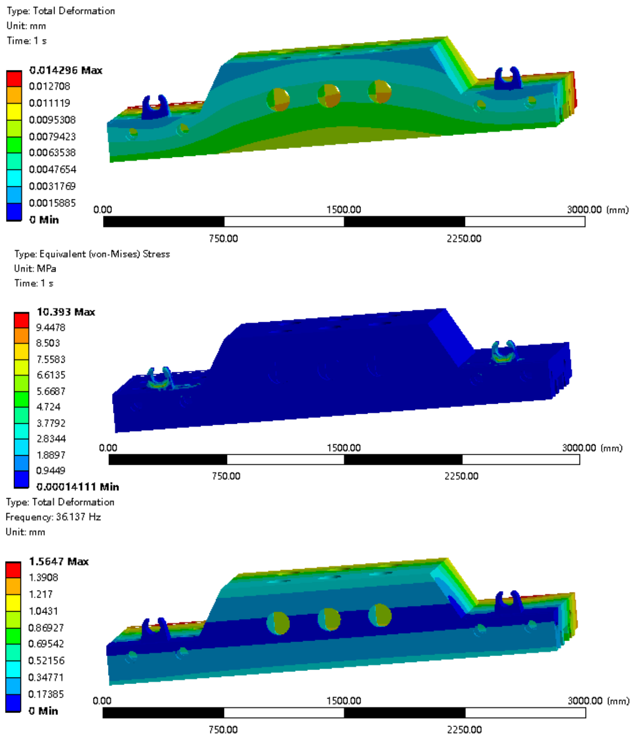

Figure 6. Finite element analysis results of crossbeam dimension optimization

The final optimization results of the beam were compared with the finite element calculation results of the original beam design, and the results are shown in the table below.

Table 6. Comparison of static and dynamic analysis before and after crossbeam dimension optimization

Optimization Objectives	Original Scheme	After Optimization	Change
Mass/kg	2187.2	1981.6	-205.6
Maximum deformation /mm	0.0286	0.0143	-0.0143
Maximum equivalent stress /MPa	11.232	10.393	-0.839
First-order natural frequency /Hz	28.686	36.137	+7.541

From the table above, it is evident that through the optimization design of the key dimensions of the selected beam design scheme, the mass of the beam has been reduced by 205.6 kg, a decrease of 9.4%; the maximum deformation has decreased by 0.0143 mm, a reduction of 50%; the maximum equivalent stress has decreased by 0.839 MPa, a reduction of 7.4%; and the first-order natural frequency has increased by 7.541 Hz, an increase of 26.29%. Both mechanical properties and vibration resistance performance have been improved. The beam designed according to the optimized design scheme has been manufactured and, upon testing, meets the usage requirements, demonstrating the reliability of the beam optimization design theoretical model, as shown in the figure below.

Figure 7. The optimal structure of a crossbeam

5. Conclusion

In this paper, the beam of a dynamic beam gantry machine tool was chosen as the research subject, and it was analyzed using finite element analysis. Due to the numerous factors affecting the static performance of the beam, the method of orthogonal experiments was employed to design the experimental combinations, effectively enhancing design efficiency. The fuzzy comprehensive evaluation method was used to optimize the beam design schemes; a combination of the entropy method and fuzzy hierarchical analysis was established to analyze the weights of the beam design indicators, and a fuzzy relation matrix was constructed, ultimately determining that Scheme 1 is the optimal solution. Through sensitivity analysis and actual production dimension rounding, the design dimensions of Scheme 1 were optimized and rounded, resulting in the specific design dimensions of the beam. Further analysis of the obtained simulation data strengthened the quantitative arguments. Through optimized design, the beam achieved lightweight, effectively improving its static performance and vibration resistance, providing a reference for the optimized design of key components of machine tools.

The paper also has its shortcomings, such as not exploring more material choices for the beam, only analyzing a single material; the objectivity of data acquisition is relatively insufficient, relying heavily on expert scoring for evaluating indicators, which leads to high dependency on experts and significant subjectivity with insufficient observability.

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