Journal of Electronic Research and Application, 2023, Volume 7, Issue 5
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

Structure Improvement and Optimization of Gantry Milling System for Complex Boring and Milling Machining Center

Zhongxin Zang[1,2]*, **Qilin Shu**[1,2,3]

[1]School of Mechanical Engineering, Shenyang Ligong University, Shengyang 110159, China
[2]Liaoning Provincial Key Laboratory of Advanced Manufacturing Technology and Equipment, Shengyang 110159, China
[3]School of Mechanical Engineering and Automation, Shenyang Institute of Technology, Fushun 113000, China

*__Corresponding author:__ Zhongxin Zang, xiaoxiongeyi@sina.com

Abstract: To enhance the efficiency and machining precision of the TX1600G complex boring and milling machining center, a study was conducted on the structure of its gantry milling system. This study aimed to mitigate the influence of factors such as structural quality, natural frequency, and stiffness. The approach employed for this investigation involved mechanism topology optimization. To initiate this process, a finite element model of the gantry milling system structure was established. Subsequently, an objective function, comprising strain energy and modal eigenvalues, was synthesized. This objective function was optimized through multi-objective topology optimization, taking into account certain mass fraction constraints and considering various factors, including processing technology. The ultimate goal of this optimization was to create a gantry milling structure that exhibited high levels of dynamic and static stiffness, a superior natural frequency, and reduced mass. To validate the effectiveness of these topology optimization results, a comparison was made between the new and previous structures. The findings of this study serve as a valuable reference for optimizing the structure of other components within the machining center.

Keywords: Machining center gantry milling system structure; Natural frequency; Stiffness; Multi-objective topology optimization

Online publication: September 25, 2023

1. Introduction

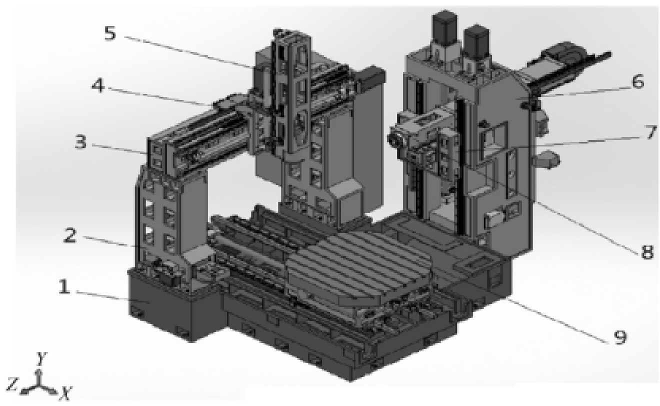
This paper focuses on investigating the gantry milling system structure of the TX-1600G complex boring and milling machining center. In line with real-world conditions, a modal was created using Solidworks, simplifying the gantry milling system structure by including the headstock beam and other milling components in various operational scenarios. Utilizing the density method in conjunction with compromise programming and efficiency function theory [1], each element's relative density within the three-dimensional (3D) mesh, as divided by Hypermesh, was chosen as the design variable. The constraint applied was a specific volume fraction.

Subsequently, the topology of the 3D mesh was optimized using the Optistruct module of Hyperworks. This optimization process resulted in a distribution diagram that highlights the optimal material placement for the gantry milling structure. The ultimate goal of this effort was to enhance the static characteristics of the gantry milling structure, thereby improving the machining precision of the boring and milling machining center.

2. TX-1600G complex boring and milling machining center structure and topology optimization mathematical model

2.1. TX-1600G complex boring and milling machining center

TX-1600G complex boring and milling machining center is a medium-sized complex machining center with independent intellectual property rights developed under the support of "National 863" program (**Figure 1**). This machining center employs a combination of gantry milling and horizontal boring techniques within a complex processing structure. Its main purpose is to manufacture intricate box-shaped components commonly found in military applications. These parts are typically processed with a single clamping, utilizing five-axis linkage for maximum efficiency.



1- bed body; 2- Milling column; 3- Beam; 4- milling table;
5-headstock; 6-boring column; 7- boring slide table;
8- Slider; 9- Working turntable

Figure 1. TX1600G boring and milling machining center model

The milling system plays a pivotal role within the boring and milling machining center, and its dynamic performance has a direct impact on the overall machining accuracy, motion stability, vibration resistance, and service life of the whole machining center [2]. Therefore, in the structural design phase, particular emphasis should be placed on prioritizing the dynamic characteristics and natural frequency of gantry milling system structure.

2.2. Mathematical model of multi-objective topology optimization

In practical engineering design, it is recognized that single-objective optimization may not effectively address diverse range of problems in practice. In this paper, the multi-objective topological optimization problem is simplified into a more manageable form using the efficiency function theory and the compromise programming method. This approach enables the attainment of a structurally advantageous layout with attributes such as reduced displacement, minimized resonance, and smaller overall volume. The efficiency function initially determines the infeasible values and optimal solutions for each sub-objective, considering the degree of achievement among these sub-objectives as a benchmark. Through a weighted methodology, the multi-objective topology optimization problem is converted into multiple single-objective topology optimization problems. Compromise programming is utilized to translate the absolute variable values from different sub-targets into a measure of similarity regarding the optimal solution for each sub-target, thereby unify the target measures of different sub-targets. Therefore, the mathematical model is selected as follows:

$$\min_{\rho=(\rho_1 \cdots \rho_n)^T} R(\rho) = 2\left\{\omega^q\left[\sum_1^m \omega_k \frac{C_k(\rho) - C_k^{min}}{C_k^{max} - C_k^{min}}\right]^q + (1-\omega)^q\left[\frac{\Lambda_{max} - \Lambda(\rho)}{\Lambda_{max} - \Lambda_{min}}\right]^q\right\}^{\frac{1}{q}}$$

If the obtained R(ρ) is smaller, the next order natural frequency and strain energy of each working condition will be higher completion degree, and closer to the optimal solution of each sub-target, then the obtained structure meets the actual requirements.

3. Working condition of gantry milling system structure

3.1. Load source and constraint of gantry milling system structure

The gantry milling system structure comprises the beam and left and right columns. When considering topological optimization for the gantry milling system structure, the primary factors to take into account are the actual load conditions and the specific requirements imposed by the complex boring and milling machining center's operation. The beam bears the external load, which includes the weight of components like guide rails and electrical equipment, in addition to its own gravitational forces. Furthermore, the beam also supports the center of gravity of milling components such as headstock and sliding table. It is important to note that the center of gravity of these components and the gantry milling system structure may not always align perfectly, leading to eccentric forces that result in torsion of the beam. This, in turn, causes the left and right columns to experience complex external forces. To address the influence of milling force, a translation calculation method for the maximum operational conditions is employed, taking into account the cutting forces detailed in the "Metal Cutting Manual" for end milling of a place [3]:

$$F_c = 6 \times 10^4 \times \frac{P_c}{v_c}$$

In milling, the cutting force in rough milling is much greater than that in fine milling, so the structure of gantry milling system under rough milling is analyzed. According to the machining center manual, the milling power can be obtained as 22.356 kW, and the vertical milling component force can be obtained as $F_{fN} = 801.12\ N$ by inserting the above formula. Longitudinal milling force is $F_f = 312.5\ N$; Transverse milling force is $F_c = 467.21\ N$. The cutting force will cause bending and torsional deformation of gantry milling system structure, thus affecting the machining accuracy.

In the finite element analysis, the beam can be regarded as a whole, the left and right columns as a whole, the gantry milling system structure is divided into three parts respectively.

3.2. Modal and static analysis of gantry milling system structure

The working stroke of the beam is 1000 mm, then it can be divided into 7 working conditions in the transverse: 830 mm, 1,030 mm, 1,230 mm, 1,330 mm, 1,430 mm, 1,630 mm, 1,830 mm. The longitudinal working stroke of the headstock is 1,000 mm, which can be divided into 5 working conditions in the longitudinal direction: 330 mm, 580 mm, 830 mm, 1,080 mm, 1,330 mm. Therefore, the orthogonal analysis of gantry milling system structure can be carried out.

Only the maximum deformation of the x and z axes is considered first. According to the analysis results, the deformation under 1,330 mm / 330 mm is the most serious, so the optimization design under the constraint conditions can meet the stiffness requirements under other working conditions.

To facilitate grid division work, finite element models for the original beam and the left and right columns were established based on their respective dimensions. It was crucial to ensure that these models retained the essential features required for the assembly of beams and columns while simplifying unnecessary elements. For instance, extraneous features such as round holes, chamfers, small bosses, sags, and similar details were omitted [4]. Additionally, material properties were assigned to the gantry milling system structure, and hexahedral mesh division was applied, along with the incorporation of boundary conditions and other necessary adjustments. The displacement contour plots for the original beam and columns can be observed in **Figures 2(A)** and **2(B)**. The first-order natural frequency modes of the original beam and the left and right columns are illustrated in **Figure 3(A)** and **3(B)**.

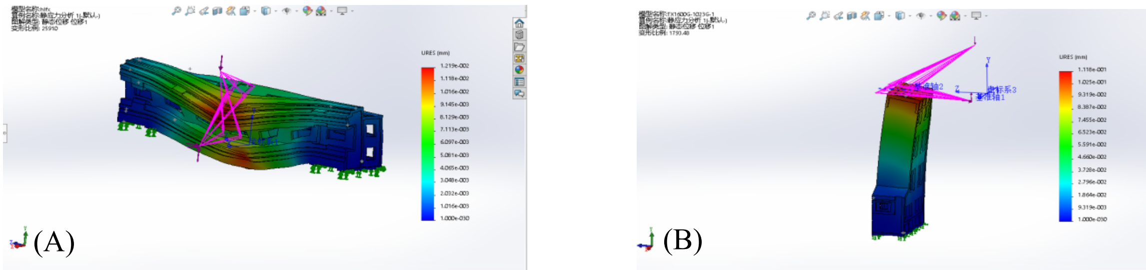


Figure 2. Static analysis cloud image of (A) the original beam and (B) the original column

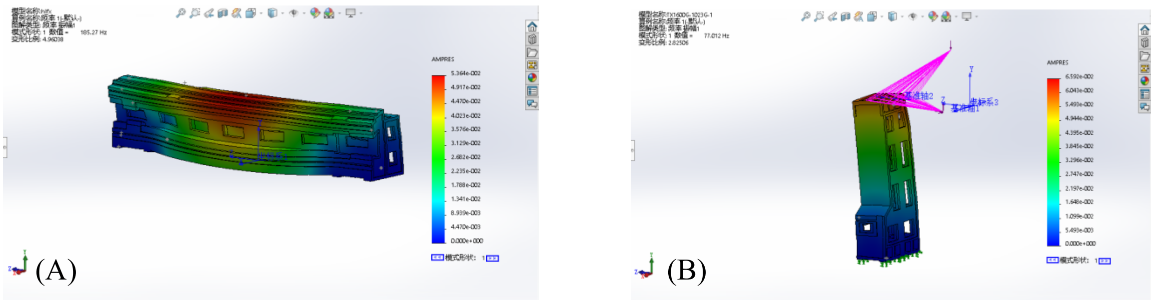


Figure 3. First order modal analysis cloud image of (A) the original beam and (B) the original column

The maximum comprehensive deformation of the original beam is 0.0122 mm. The first natural frequency of the original beam is 185.270 Hz. The maximum comprehensive deformation of the original left column is 0.1118 mm; The first natural frequency of the original left column is 77.012 Hz. The above data were inserted into the mathematical model to prepare for the next step of multi-objective topology optimization.

4. Structural topology optimization of gantry milling system

This paper employs a combination of the compromise programming method and the efficiency function method to enhance the stiffness and first natural frequency of the gantry milling system within the TX-1600G complex boring and milling machining center. To achieve this, the strain energy and the first-order natural frequency of the original beam and left column were processed to standardize their performance parameters. These processed values, namely the strain energy and the first-order natural frequency, were designated as the design variables for the comprehensive objective function, facilitating the topology optimization of the gantry milling system [5].

For each individual objective, the ideal value was substituted into the mathematical model, and the objective function aimed to minimize this mathematical model. Modal analysis of the model post-optimization revealed a ω-weight ratio of 0.44 for the beam and 0.45 for the left column, both subject to a specific volume fraction constraint.

Following 80 iterations for the beam, the model reached an optimal value of 0.03, and the corresponding density cloud map was generated (**Figure 4A**). Similarly, after 57 iterations for the left column, an optimal model value of 0.41 was achieved, accompanied by the generation of a density cloud map (**Figure 4B**).

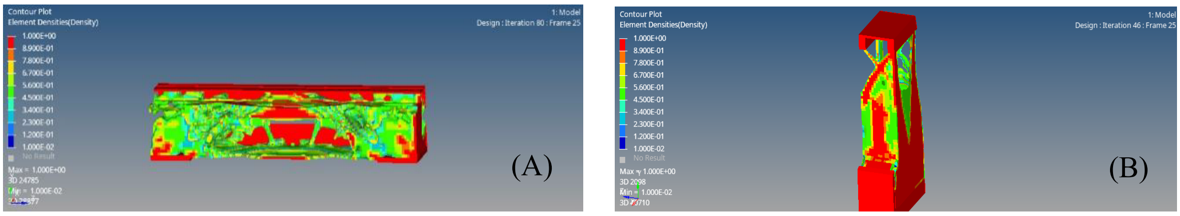


Figure 4. Spectacular topology optimized density cloud image of (A) the beam and (B) the column

5. New structural modeling of gantry milling system

In the process of re-modeling the gantry milling system structure, two guiding principles are adhered to, taking into account the distribution of the density contour for both the beam and the left column: (1) Maintain the original assembly relationship between the new model and other components, while modifying the distribution of reinforcement plates and the internal cavity's shape within the structure; (2) Align the distribution structure of stiffened plates within the design area as closely as possible to the corresponding density contours obtained from the structure's topology optimization. This alignment ensures that the performance parameters of the newly designed structure are in sync with the ideal values and guarantees the quality of the new structure [6-8]. Following several iterations of modeling improvements, static analysis, and modal analysis, the new beam structure for the gantry milling system of the TX-1600G complex boring and milling machining center, as designed in this paper, is shown in **Figure 5(A)**, and the new column structure is shown in **Figure 5(B)**.

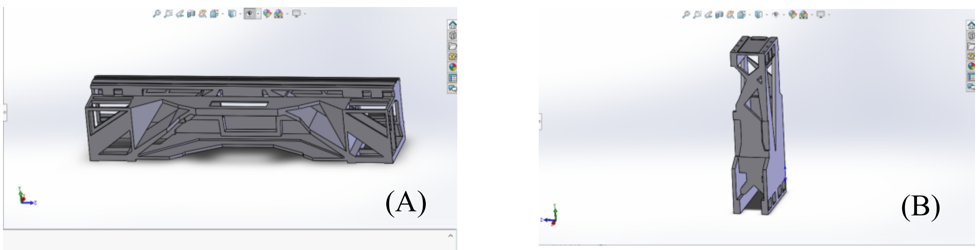


Figure 5. Structure drawing of (A) the new beam and (B) the new column

6. Performance comparison before and after structure of gantry milling system

The displacement contour plots from static analysis for the newly optimized and reconstructed gantry milling system structure can be observed in **Figure 6(A)** and **(B)**. Meanwhile, the first-order natural frequency mode illustrations are provided in **Figure 7(A)** and **(B)**. Additionally, **Table 1** presents the structural performance parameters of the gantry milling system.

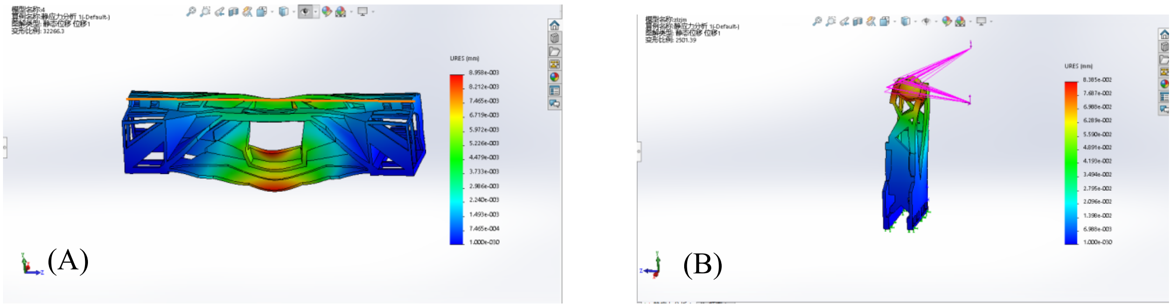


Figure 6. Static analysis cloud image of (A) the new beam and (B) the new column

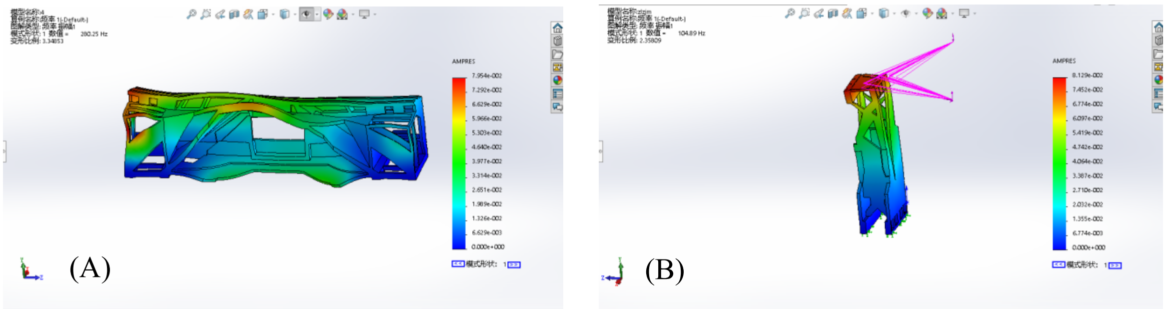


Figure 7. Cloud image of first-order modal analysis of (A) the new beam and (B) the new column

Table 1. Comparison of structure and performance parameters of gantry milling system

Structure component	Before and after optimization	Maximum deformation (mm)	First natural frequency (Hz)	Quality
Beam	Before optimization	0.01219	185	2838kg
	After optimization	0.008958	280	2366kg
	Degree of improvement	-25.13%	34%	-16%
Post	Before optimization	0.1118	77	2110kg
	After optimization	0.08385	105	1809
	Degree of improvement	-25%	27%	-14%

Table 1 provides conclusive evidence of the improved mechanical characteristics of both the beam and the column within the gantry milling system structure. Specifically, the beam exhibits significantly reduced deformation, even under the most demanding operational conditions when the headstock is positioned at the beam's midpoint. Moreover, there is a substantial increase in the first-order natural frequency for each component. As these performance parameters are improved, the overall weight of the gantry milling system structure is significantly reduced, resulting in lowered manufacturing costs. These improvements collectively contribute to the smoother operation of the compound boring and milling machining center and lead to heightened machining precision within the machining center.

7. Conclusion

In this paper, a novel gantry milling system structure is designed using the topology optimization method, which incorporates both the compromise programming method and the efficiency function method. The resulting structure exhibits superior performance parameters while maintaining reduced overall weight. This not only leads to cost savings but also enhances the machining accuracy of the complex boring and milling machining center by improving the dynamic and static characteristics of the gantry milling system structure. Furthermore, this paper underscores the advantages of multi-objective topology optimization technology in structural design, showcasing its potential for various optimization projects. The findings here can serve as a valuable reference for the topology optimization design of different components and structures.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Zhang J, Shu Q, Wang G, 2016, Design of Electronic Control System of Disc Tool Library Based on PLC. Machine Tool & Hydraulics, 44(14): 129–132.

[2] Kang J, Wang J, Liu A, et al., 2014, Study on Deflection Analysis and Compensation Method of Slider for Boring and Milling Machining Center of TX1600G. Modular Machine Tool & Automatic Manufacturing Technique, 8(4): 12–17.

[3] Shanghai Metal Cutting Technology Association. Metal Cutting Manual. 2004, Shanghai Science and Technology Press, Shanghai.

[4] Tian X, Song F, Song B, et al., 2009, Experimental Modal Analysis of Vertical CNC Milling Machine. Machine Tool & Hydraulics, 37(12): 42–44 + 51.

[5] Wang X, Jia Z, Yang F, et al., 2009, Topology Optimization Design and Analysis of Beam Components in Gantry Machining Center. Manufacturing Technology & Machine Tool, 2009(11): 64–68.

[6] Bendse MP, 1989, Optimal Shape Design as a Material Distribution Problem. Structural and Multidisciplinary Optimization, 1(4): 193–202.

[7] Wu W, Yang DZ, Huang YY, 2008, Topology Optimization of a Novel Stent Platform with Drug Revervoirs. Medical Engineering and Physics, 30(9): 1177–1185.

[8] Aenlle ML, Brincker R, 2013, Modal Scaling in Operational Modal Analysis Using a Finite Element Model. International Journal of Mechanical Sciences, 76: 86–101.