

Multi-objective Structural Optimization of Column based on Topology Optimization and NSGA- II Algorithm

Chongqing Li

Army Academy of Armored Forces, Changchun, China

Abstract: In order to realize the lightweight design of CNC machine tool and optimize the important structural columns in gantry structure, this paper proposes a combination of variable density topology optimization and multi-objective optimization based on NSGA-II algorithm, which realizes the pursuit of lighter and better structure without changing the performance of the columns, and also puts forward suggestions and improvement directions for the subsequent optimization direction. A new theoretical basis for structural optimization is proposed.

Keywords: Column; Lightweight; Topology Optimization; NSGA-II Algorithm.

1. Preface

With the concept of intelligent manufacturing, factories began to develop to unmanned and intelligent. As a key link in intelligent and unmanned chemical plants, CNC machine tools have gradually been put forward new requirements. CNC machine tools are no longer confined to large factories, but are more used in college laboratories, process offices and other small places, which requires the machine tool in the case of precision does not reduce, reduce the volume and weight of the entire machine tool, in order to more portable processing in various places.

Since 1948, when the first CNC milling machine was successfully developed, the machine tool has opened up new fields. And in 1952, the concept of three-axis CNC machine tools officially landed, at this time the processing accuracy has reached the precision level, and the control mode has officially evolved from the "manual era" to the "automatic era". With the adjustment of tools, structural types and dimensions, CNC machine tools gradually develop in the direction of "small", "fine" and "stable", but subject to materials, process technology and other aspects of the situation, the size of the machine tool is also gradually stable in a stable range, encountered a bottleneck.

With the proposal of the national policy, the mechanism of the machine tool has gradually developed to the lightweight design. Compared with the cost problems caused by the lightweight of materials, the lightweight design of the mechanism is more in line with the development of The Times. Relying on the finite element theory and using virtual modeling and simulation technology, the speed of structural optimization is accelerated, while avoiding a lot of trial and error time caused by unreasonable design and structural design direction modification, the time cost of optimization is compressed, and the development cycle is reduced.

High precision CNC mechanism is mainly based on gantry structure, general beam and column are the main optimization objects, this paper will choose the column as the research object for structural optimization.

2. Structure Optimization Theory

2.1. Principle of Optimal Design

Usually structural optimization, in fact, is to establish a mathematical model, by adjusting the aspects that can be directly changed in the structure (x_i), such as shape and internal size, which is called independent variables, in the requirements of these independent variables or the performance parameters of the structure to be limited, such as strength, hardness, quality, volume, etc., this is called constraints (G_i, S_i), continuous adjustment, The optimization finally achieves the desired goal, that is, the functional goal.

$$\begin{cases} x_i \\ G_i \geq b \\ S_i \leq A \\ M \max/min \\ (i=1, 2, \dots, n) \end{cases} \quad (1)$$

If only one performance index of the column is used as the optimization target (such as total deformation, first-order natural frequency or quality), there is a problem that the current optimization target is optimized while other performance is decreased. If multiple objectives are optimized separately, the optimization objectives interfere with each other, and the optimal solution cannot be reached. In order to improve the static performance of the optimized structure while making it lightweight, topological optimization method and multi-objective method will be used to optimize the design.

2.2. Topology Optimization Theory

Topology optimization is a kind of internal analysis of the whole component with the static and dynamic characteristics of the studied component as the constraint condition to find a better optimization method of material distribution. The usual optimization methods are ICM method, variable density method and homogenization method.

Since the research object of this paper is the column, the column is usually based on cuboid shape, so the variable density method will be used for research, that is, the structure is first dispersed into a finite number of small units, and the difference between the density and elastic modulus between

the units is used as the design variable to seek the optimal solution.

$$E_i = x_i^p E_o \quad (2)$$

- E_i -- the elastic modulus of unit i ;
- E_o -- elastic modulus of unit materialization;
- P -- penalty factor;
- x_i -- Relative density.

When the formula (2) is used, when the relative density is equal to 1, it means that it needs to be an entity and bear the load; on the contrary, the relative density is 0, it means that no entity is needed. By controlling the penalty factor, the parts with relative density between 0 and 1 are rationally allocated to optimize the material distribution.

2.3. NSGA-II Algorithm

NSGA-II algorithm compares the advantages and disadvantages of the target solutions in the algorithm optimization process based on the non-dominant sorting criterion and the congestion comparison criterion, and selects the high-quality solutions in the solution by the elite optimization method [1], which solves the problem of low quality in the algorithm optimization process, and thus greatly improves the overall performance of the algorithm. Moreover, pareto frontier solution has better uniformity and distribution, and is easy to select.

Specific calculation steps of NSGA-II algorithm [2]:

- 1) Determine that the initial population number is M , the mutation rate is b , the crossover rate is j , and the evolutionary algebra is N ;
- 2) The initial population of M was randomly selected;
- 3) The current population was stratified by the fast non-dominant intensity ranking method, and the current generation was selected, crossed and mutated, and M new individuals were selected to form a new subgroup. The parent's elite subgroup and the new subgroup were fused to produce a new population of $2M$;
- 4) The new population needs to be treated by elite, the parent population needs to be sorted by fast non-dominance, and the new parent population is determined by calculating and arranging according to the current generation crowding comparison operator;
- 5) Need to judge the algebra ($i=N$), if it is true, then stop the calculation and output the result; If $i \neq N$, return to Step 2) to continue the calculation until the algebraic requirements are met, the algorithm is aborted, and this output data is the final data.

2.4. Multi-objective Optimization based on NSGA-II Algorithm

Multi-objective optimization based on NSGA-II algorithm, the independent variable is the size parameter of the column, with the total deformation and first-order modal frequency as the constraint conditions, and the quality as the target condition for multi-objective optimization, to ensure that the performance is not reduced at the same time to achieve the lightest mass and optimal structure.

3. Column Structure Optimization

In this paper, variable density method is adopted for optimization. Firstly, an optimization model is established to divide the design region and the non-design region. A minimum column volume is established with the material density of the design area as the design variable and the

displacement under the load force as the constraint condition. The optimization results of convergence of 30 iterations are selected as shown in the figure below.

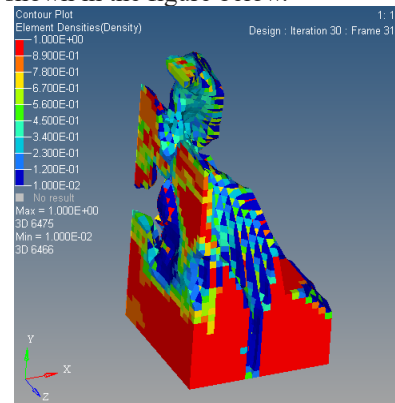


Fig 1. Column 30th optimization result

According to the color of the optimized structure model, it can be seen that the base and middle area of the column bear the main load force and need to be retained and strengthened. The blue area in the figure indicates that the load force is small, which can be eliminated or narrowed or thinned. Also pay attention to the bottom, middle and top reinforcement connections. In this way, the main structural form of the column can be basically determined.

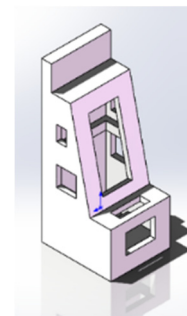


Fig 2. New columns in the topology

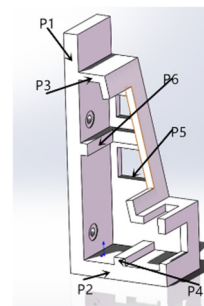


Fig 3. Column independent variable dimensions

The key structure size is selected as the independent variable from the new column after topology optimization by variable density method, and the variation range of the independent variable is limited according to the actual situation. Then, the total deformation and first-order modal frequency are taken as the constraint conditions, and the lightest mass is pursued as the objective function to establish the optimization function.

Using finite element analysis software, the samples were selected by space first filling design, and 10 groups of samples were randomly selected for iterative optimization. The 6-10-3 BP neural grid was established by using 3-layer neural network for sample optimization. In order to prevent

the final sample error from being too large, the data is normalized to design the learning rate, training error and training frequency, and the expected error of the final data is controlled within 5% to ensure the rationality of the data.

Based on NSGA-II algorithm, the column multi-objective

optimization sample is selected according to the constraint conditions and the weight ratio of the objective function. Because the actual processing capacity is not considered in data optimization, the data organization needs to be rounded, and the final optimization results are as follows.

Table 1. Comparison between the scheme after the round of the column and the original structural performance

Design variable	Original scheme	Option 1	Contra-ratio/%	Option 2	Contra-ratio/%	Option 3	Contra-ratio/%
m/kg	1.514	1.5006	-0.89	1.4987	-1.02	1.4998	-0.93
δ_{max}/mm	0.0012641	0.0010926	-13.5	0.0010949	-13.4	0.0010944	-13.4
f_1/hz	1168.7	1512.6	29.4	1512.7	29.5	1517.4	29.8

It can be seen from the data that the three optimization results are very close to each other, so it is necessary to conduct data analysis according to the weight ratio of performance. In scheme 2, the weight is the lightest, while the total deformation and first-order mode frequency are not much different from the other two groups, so it is the optimal scheme.

4. Direction of Improvement

The column is optimized by topological optimization and multi-objective optimization method based on NSGA-II algorithm, and the temporary optimal solution is obtained. Through the above experimental analysis, it can also be optimized in the following aspects:

4.1. Optimization of Algorithm

In this paper, NSGA-II algorithm is adopted, which is good for small-capacity data, but still has shortcomings for a large number of constraints. Therefore, in order to ensure the overall level of performance, more advanced and more adaptive algorithms can be used for optimization, and the target results may be better.

4.2. Structure Type

In this paper, the structure is designed by means of normal reinforcement under the condition of topology optimization. At present, there are a large number of structure types such as tortoise-shell type, honeycomb type, rice type and O type. These types can often achieve higher technical performance

in a thinner, narrower structure, so you can experiment with new structures.

4.3. Performance of Finite Element Analysis

In this paper, the main constraint conditions for structural performance are total deformation, first-order mode frequency, etc. In fact, CNC machine tools also need thermal performance analysis, dynamic performance analysis, etc., so structural optimization should also ensure that all performance parameters can be used as constraints to ensure the optimal performance.

5. Closing Remarks

In this paper, the gantry CNC milling machine is taken as the research object, and the optimal structural parameters are obtained through topology optimization and multi-objective optimization based on NSGA-II algorithm, which opens a new idea for the column structure optimization and puts forward more schemes for the column optimization theory.

References

- [1] LI H Z. Improvement of NSGA2 genetic algorithm and its application in microgrid configuration [D]. Lanzhou University of Technology,2017.
- [2] Lai Wenxing, Deng Zhongmin, Zhang Xinjie. Structural dynamics model confirmation based on multi-objective optimization NSGA2 algorithm [J]. Chinese Journal of Computational Mechanics,2018,35(06):669-674.