Bionic Design for Column of Gantry Machining Center Using Honeycomb Structures

Yuhong Zhang, Wenhua Ye, Sheng Leng , and Wenyong Shan

Abstract— **With the aim to improve the machining precision of a gantry machining center, bionic optimization design for ribs structure of its column was investigated. Firstly, based on the analysis of honeycomb structures, three kinds of bionic columns were discussed and simulated by finite element analysis method. The column structure with the best comprehensive performance was achieved according to the column design optimization system using the Gray Analytic Hierarchy Process. The bionics principles for ribs of column were concluded, which provided a new method for improving the traditional design and achieving comprehensive performance optimization structures of machine tool components.**

Index Terms—**bionics design, honeycomb structures, analytic hierarchy process, gantry machining center, finite element analysis**

I. INTRODUCTION

After 2 billion years of natural selection optimization, biological structure was almost perfect and wonderful, provide a lot of design prototype and creative improvement methods in order to solve engineering technical problems for human [1].

Bionic design of the mechanical function and structure based on the study of the mystery and mechanism of biological structure is one of the core contents of the mechanical bionic design. Stiffness was an important index of machine performance. It not only influenced the precision and surface quality of work piece, but also affected vibration resistance, noise and movement stability of the machine tool [2]. In addition, moving components in high speed machine tool with high acceleration should have light weight and strong vibration resistance, then we could use least amount of materials to suffer the biggest load [3].There are many organisms of high specific stiffness in biosphere with its unique structural features. Applying some kind of rules and mechanism of the bionic structure is a method of improving the specific stiffness of structure. In recent years many scholars had applied the bionic structure to optimization design of machine tool structure. For example, Ling Zhao, Wuyi Chen [4] used hollow sandwich structure of organism to the bionic design on ribs arrangement of machine table. Yongbin Yang [5] studied the advantages of the biologic skeleton which increased the stiffness of organism, finding that the biologic skeleton indicated the best path for organism to suffer the load. The inner structure of column was redesigned as skeleton to improve the specific stiffness. Ling Zhao [6] carried out structure optimization design for ribs of a gantry machine tool cross-beam based on giant waterlily vein distribution, and summarized the bionic design principles of cross-beam's ribs.

There are great advances in the bionic structure. In the area of the design of machine tool, most studies are on basis of one single kind of structure with some biological characteristics without consideration of derivative structures. To obtain a structure with best performance, it is necessary to investigate varieties of bionic structure. So far, its application in the structural design of machine tool is in the stage of preliminary and experimental research because of the imperfection of pilot study on the bionic structure.

Aiming to improve comprehensive performance of column of large-scale gantry machining center, the lightweight and high efficiency biological structure configuration law was studied which is applied to the design of ribs of column. The solutions were optimized by the Gray Analytic Hierarchy Process (Gray-AHP). The results show that applying the bionic design method could improve the comprehensive performance of column.

II. THE BASIC DESIGN METHOD OF THE BIONIC STRUCTURE

Based on thoroughly understanding the structure and function mechanism of organism, we selected bionic object, study similarities between the large-scale machine structure and biological structure, and then set up the bionic organisms prototypes, and optimized the structure of the designing object. Because the biological structure was more complex than machine structure, we must consider manufacturability of the components, when collecting the features structures which influenced its mechanical properties.

In this paper, a parameterized model based on studying organism structure, was set by the 3d CAD software, with construction form and size of typical structure of large-scale machine tool. We used ANSYS software for simulation of column, and then according to the simulation results and

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other aspects of performance, we used Gray-AHP for optimization to get the structure of column with comprehensive performance. The process was shown in figure 1.

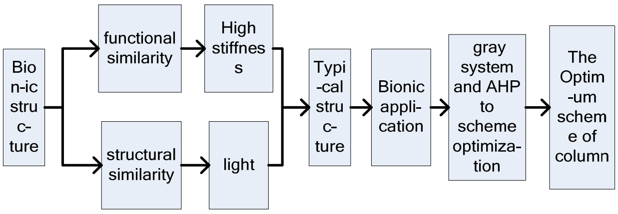

Fig. 1 Column Bionic Design Flow Structure

III. BIONIC DESIGN AND ANALYSIS OF COLUMN

A. *Analysis of column*

The research object was a kind of column of precision gantry machining center (as shown in figure 2). Its material was gray iron HT300. The column was the support parts of machine tool, supporting beam of machine tool, cross slide, box and sliding base. The load was large. In addition, big deformation of column would directly affect processing precision of parts. Therefore assuring that column had greater ability to resistant to deformation is very important under the big dynamic and static load.

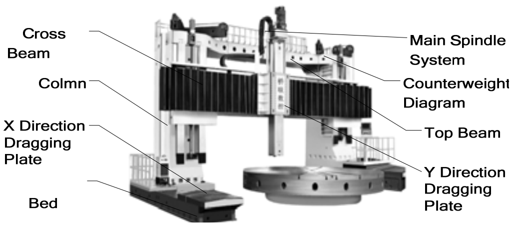

Fig. 2 A Large Gantry Machining Center

After determination of shape and materials, changing the internal structure of the column had significant influence on improving the stiffness and reducing deformation, especially for castings of machine tool. The traditional designing form of ribs were too simple, such as parallel,"#" shape, "X" shape or other simple shapes[7]–[9]. As shown in figure 3, it was the typical "X" shape arrangement for ribs of column of gantry machining center. The study found that we could improve dynamic and static characteristic by changing arrangement of ribs and structure parameters. So we decided to redesign and optimize of ribs based on thinking of the bionic structure.

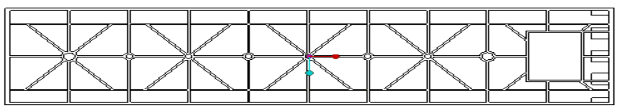

Fig. 3 The Arrangement of Ribs of a large Gantry Machining Center Column

B. *Research of biology performance*

The bee hives that built with wax was light and strong. They were beautiful and practical buildings [10]. Honeycomb structures originated from the basic structure of bees hives (figure 4). From the outside, the small holes in hives were hexagonal, which were arranged close together. Each hole was not exact hexagonal prism, because the bottom was not flat. There were three equal tapered diamond prism, each of the diamond obtuse angle was $109°\ 28'$, the acute angle was $70°\ 32'$.The volume of each hole was almost $0.25\,cm^3$. Walls of hives were thin and less than 0.1 mm on average [11]. To against the maximum load, the bottoms of nest room were mutually combined.

Honeycomb structure, with high specific stiffness, high specific strength, light weight, excellent heat and sound insulation, widely applied in structure of construction, industrial boiler, aircraft and so on. For example glass fiber reinforced plastic honeycomb sandwich structure that the plane applied had advantages of high specific strength, high structure stiffness, light weight, easy molding that were suitable for materials of making wing of small UAV[12]. Honeycomb core was now applied in cast-in-place concrete building, The hollow wall of honeycomb structures was applicable to the new floor system of large span and large space, not only with light weight, good seismic performance, good sound insulation effect, but also material saving. It was really the economic one [13].

We were quite familiar with the traditional single honeycomb shape structure, such as triangle honeycomb (as shown in left part of figure 5), hexagonal honeycomb. What was so special to deserve to be mentioned, a kind shape of "combination of honeycomb " called Kagome honeycomb (as shown in right part of figure 5) which was widely caused the attention in recent years, Kagome honeycomb [14] comprised of hexagonal honeycomb and triangle honeycomb.

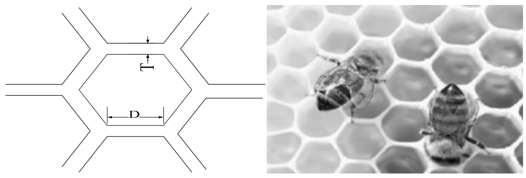

Fig. 4 Hexagonal Honeycomb

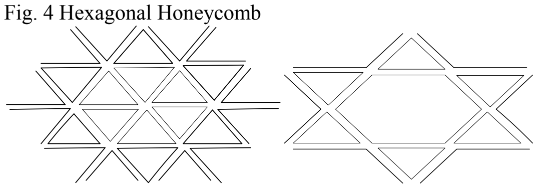

Fig. 5 Triangle and Kagome Honeycomb

C. *Bionic design of column*

The development direction of modern numerical control machine tool was high speed and high precision, moving components in high speed machine tool with high acceleration should have light weight and strong vibration resistance, then we could use least amount of materials to suffer the biggest load. According to the above specific stiffness of honeycomb structures, we tried to change internal evenly arranged ribs of column to honeycomb structures, which could improve the comprehensive performance of column.

Therefore, by combining with processing manufaturability and changing the ribs of column prototype, three bionic type of ribs structure were put forward as shown in table Ⅰ， in order to study law of column structure performance which influenced by arrangement of ribs.

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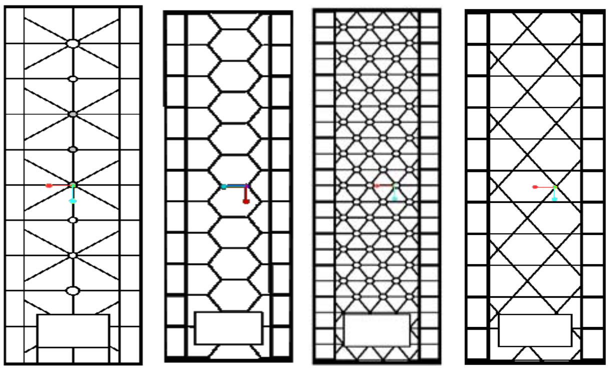
TABLE I
PROTOTYPE COLUMN AND THREE BIONIC TYPE OF STIFFENED PLATE

TYPE	Structure Characteristics
Prototype (first scheme)	The form of ribs is "X" shape
Bionic Ⅰ type (second scheme)	The form of ribs is "hexagonal honeycomb" shape
Bionic Ⅱ type (third scheme)	The form of ribs is "triangle" shape
Bionic Ⅲ type (fourth scheme)	The form of ribs is "kagome" shape

Based on satisfying the design requirements of machine tool column, by designing the three type of bionic ribs, thickness of ribs and thickness of the prototypes were much close, and the number of reinforced mesh of bionic Ⅰ type was close to that of the prototypes. Bionic Ⅱ and bionic Ⅲ was transformed in the basis of bionic Ⅰ. In PROE model, we could get the following four schemes (as shown in figure 6). We need optimize these schemes. The purpose of optimization was selecting the best design of machine tools column through comparing and analyzing various optional design of machine column, in order to make the comprehensive performance of machine tool column best. Static performance, vibration resistance, light weight, manufacturing technology and economic performance were required to be considered during column of machine tool design, to meet the development request of modern CNC machine tool products with light weight, performance optimization, manufacturability and economical efficiency. As it was a multi-objective optimization decision problem, a reasonable effective optimization model need to be established.



First Scheme Second Scheme Third Scheme Fourth Scheme

Fig. 6 Design Scheme of Machine Tools Column

D. *Finite element analysis of column structure*

We built four kinds of column model for the gantry machining center in the 3d CAD software. The structure of post was simplified, and the structure of the bolt holes and small round holes, chamfering and small fillet, small steps were all removed. Then import the 3d model of machine tool column into ANSYS software to analyze the mechanical characteristics of ribs structure [15].Columns were the support parts of machining center, bearing the weight of the beam and cross slide, sliding base, balance weight of spindle system, and the cutting force. Barb bolt of column bottom was fixed connected to lathe bed. So applied fixed constraint on the bolt place, and applied frictionless constraints on the bottom of column to limit normal movement.

Through static and modal finite element analysis of column, we got index value of static performance, vibration resistance and lightweight of all kinds of schemes. It was shown in table Ⅱ after statistical collect.

Choosing the traditional column structure scheme was mainly based on experience of designer selection, it was difficult to ensuring that the selected design plan was the best one. In order to solve this problem, this paper used the Gray-AHP to choose the best comprehensive performance of column structure of column of the machine tool.

TABLE Ⅱ
INDEX VALUE OF STATIC PERFORMANCE, VIBRATION RESISTANCE AND LIGHTWEIGHT OF ALL KINDS OF SCHEMES

Performance index		First scheme	Second scheme	Third scheme	Fourth scheme
Static perfor-mance	Maximum stress /MPa（cost）	13. 42	40. 03	6. 54	7. 82
	Maximum deformation /μm（cost）	204	173	122	136
Vibra-tion resis-tance	First step inherent frequency /Hz（efficiency）	29. 81	33. 45	29. 56	30. 73
	Second step inherent frequency /Hz（efficiency）	42. 76	46. 22	41. 47	42. 92
	Third step inherent frequency /Hz（efficiency）	68. 12	75. 72	71. 75	71. 48
	Forth step inherent frequency /Hz（efficiency）	98. 69	106. 91	105. 36	103. 36
Light-weight	Mass of column/Kg（cost）	15069	15273	19878	15818
	Height of center of gravity of column/mm（cost）	2591	2616	2568	2573

IV. THE BASIC THEORY OF GRAY-AHP

Gray-AHP includes two main contents: apply the AHP for the weight of the evaluation indexes and apply the grey theory for the comprehensive evaluation of indexes.

A. *Apply the AHP for the weight of the evaluation indexes*

Applying AHP to analyzing problem need *three* steps in general:

1) The establishment of AHP structure model

2) Construct the judgment matrix

We could use Delphi method to determine judgment matrix A by many experts, this evaluation matrix required experts to form the relative importance judgement of the indexes, the elements of matrix should be filled based on the definition of tableⅢ. Evaluation matrix A was equation (1).

$$A = \begin{bmatrix} w_1 / w_2 & \cdots & w_1 / w_n \\ \vdots & & \vdots \\ w_n / w_1 & \cdots & w_n / w_n \end{bmatrix} \quad (1)$$

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TABLE III
MATRIX JUDGMENT SCALE (1 ~ 9 SCALE METHOD)

Scale	Meaning
1	Show that the two elements is compared with the same importance
3	Show that the two elements is compared , the former slightly more important than the latter
5	Show that the two elements is compared , the former obvious more important than the latter
7	Show that the two elements is compared , the former extremely more important than the latter
9	Show that the two elements is compared , the former strong more important than the latter
2,4,6,8	Show that middle value of the adjacent judgement

3) The check of consistency

B. Apply the grey theory for comprehensive evaluation of indexes

The main steps of comprehensive judgment which involved two layers were: the determination of evaluation indexes, the determination of the optimal index set, the dimensionless processing of data, the determination of the judgment matrix, the determination of each weight, the comprehensive evaluation of the second layer, the comprehensive evaluation of the first layer (grey comprehensive evaluation).

1) The determination of the reference sequence

When using gray incidence method to do the comprehensive evaluation, the evaluation criterion was the optimal value among indexes. When the index belonged to "efficiency" index, we took the maximum value of each scheme; when the index belonged to "cost" type index, we took the lowest value of each scheme. Reference Series was denoted by equation（2）:

$$X_0(k)=\{X_0(1),\ X_0(2),\ X_0(3),\cdots,X_0(k)\} \quad (2)$$

2) The determination of collection of the optimal indexes

The optimal index set was an aggregate that consists of the optimal index of the evaluating objects，and it was also reference series of the evaluation compared objects. The optimal indexes set E * (namely reference sequence $X_0(k)$) and the indexes of the evaluation objects composed matrix E.

$$E=\begin{bmatrix} e_1^* & e_2^* & \cdots & e_m^* \\ e_1^i & e_2^i & e_k^i & e_m^i \\ \vdots & \vdots & & \vdots \\ e_1^n & e_2^n & \cdots & e_m^n \end{bmatrix}^T \quad (3)$$

In this equation: e_k^i was the original value of the kth index in the ith evaluation object. $E^*=\left|e_1^*,e_2^*,\cdots,e_m^*\right|$ was the optimal indexes set.

3) Dimensionless processing of the data

For compare, the following equation (4) was used to nondimensionalize the optimal indexes set and the indexes set
of each scheme in order to reduce the interference of random factors:

$$e_i^{(1)}=\frac{e_i^{(0)}}{\overline{e_i}} \quad (4)$$

In this equation: $e_i^{(0)}$, $e_i^{(1)}$ respectively standed for the original data of the evaluation indexes and the nondimensionalization data; $\overline{e_i}$ was the average value of the ith index .

4) The determination of judgment matrix

According to the grey system theory, we could obtain the ith evaluation object and the gray incidence coefficient of the kth index from equation （5）[16]:

$$t_i(k)=\frac{\min\limits_i\min\limits_k\left|e_k^*-e_k^i\right|+\rho\times\max\limits_i\max\limits_k\left|e_k^*-e_k^i\right|}{\left|e_k^*-e_k^i\right|+\rho\times\max\limits_i\max\limits_k\left|e_k^*-e_k^i\right|} \quad (5)$$

In this equation: ρ was resolution ratio, generally took 0.5,i=1,2,⋯,m, k=1,2,⋯,n

Evaluation matrix consisted of correlation coefficient:

$$T=\begin{bmatrix} t_1(1) & t_1(2) & \cdots & t_1(m) \\ t_2(1) & t_2(2) & \cdots & t_2(m) \\ \vdots & \vdots & & \vdots \\ t_n(1) & t_n(2) & \cdots & t_n(m) \end{bmatrix} \quad (6)$$

5) The determination of weight

Using AHP method to determine weight coefficient vector Q of the evaluation index on all layers, two layers of comprehensive evaluation weight coefficient vector were Q_A and Q_B respectively.

6) The second layer of grey comprehensive evaluation

The evaluation matrix of the second layer:

$$L=Q_B\times T \quad (7)$$

7) The first layer of comprehensive evaluation

The first layer directly made use of the second layer evaluation results to compose the first layer of judgment matrix L. Grey comprehensive evaluation results vector was:

$$R=Q_A\times L \quad (8)$$

V. COLUMN OPTIMIZATION PROCESS BASED ON GRAY-AHP

A. The establishment of comprehensive performance of column and AHP model of machine tools

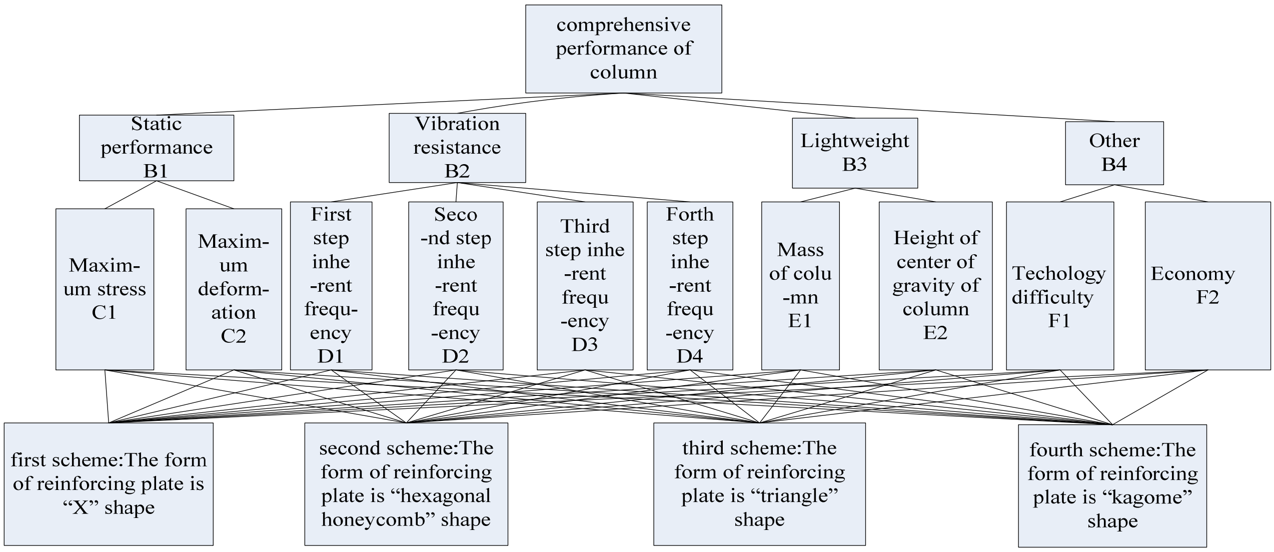

Fig. 7 The Appraisal Index Set of Column Scheme and Evaluation Hierarchical Model

Multi-objective comprehensive capability analysis and scheme evaluation process of column structure of gantry machining center was based on Gray-AHP, which defined general objective layer of hierarchical model was comprehensive ability of column. Sub-goals layer consisted of the static performance, vibration resistance, lightweight and other indexes; Index layer was maximum stress, maximum deformation, the first step inherent frequency, the second step inherent frequency, third step inherent frequency, fourth step inherent frequency, mass of column, height of center of gravity of column, technology difficulty and economy; Scheme layer included these forms: the form of ribs was “X” shape, the form of ribs was “hexagonal honeycomb” shape, the form of ribs was “triangle”, the form of ribs was “Kagome” shape. So far, we established evaluation hierarchical model, as shown in figure 7.

B. Construct judgment matrix and calculating weight

Because of importance of evaluation index to evaluation goal was different, each index was given different weight coefficient.The more important the weight coefficient of indexes were, the bigger they were. This paper used the Delphi method (experts consult method), and requested experts to fill in five evaluating matrix for column scheme according to the requirements, respectively was:

Matrix A-Bi: the relative importance of four indexes of sub-goals layer to having influence on the total target;

Matrix B1-Ci: relative to the static performance, the relative importance between the maximum stress and maximum deformation;

Matrix B2-Di：relative to vibration resistance, the relative importance among the first step inherent frequency, the second step inherent frequency, third step inherent frequency and fourth step inherent frequency；

Matrix B3-Ei：relative to lightweight, the relative importance between mass of column and height of center of gravity of column.

Matrix B4-Fi: relative to other, the relative importance between technology difficulty and economy.

The data which experts evaluated in accordance with AHP was processed, matrix that passed the inspection form matrix weight vector based on maximum eigenvalue method. The matrix and weight vectors was shown in table Ⅳ ~ Ⅷ.

TABLE Ⅳ
JUDGMENT MATRIX A-BI AND WEIGHT

A	B1	B2	B3	B4	Weight QA
B1	1	1	2	3	0.3529
B2	1	1	2	3	0.3529
B3	1/2	1/2	1	3/2	0.1765
B4	1/2	1/3	2/3	1	0.1176

TABLE Ⅴ
JUDGMENT MATRIX B1-CI AND WEIGHT

B1	C1	C2	Weight QB1
C1	1	2/5	0.2857
C2	5/2	1	0.7143

TABLE Ⅵ
JUDGMENT MATRIX B2-DI AND WEIGHT

B2	D1	D2	D3	D4	Weight QB2
D1	1	2	2	2	0.3889
D2	1/2	1	2	3	0.2995
D3	1/2	1/2	1	2	0.1881
D4	1/2	1/3	1/2	1	0.1235

TABLE Ⅶ
JUDGMENT MATRIX B3-EI AND WEIGHT

B3	E1	E2	Weight QB3
E1	1	3	0.75
E2	1/3	1	0.25

TABLE Ⅷ
JUDGMENT MATRIX B4-FI AND WEIGHT

B4	F1	F2	Weight QB4
F1	1	3	0.75
F2	1/3	1	0.25

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C. The second layer of comprehensive evaluation

Professional according to "very easy, very good" as the five points, "more easily, better" as four points, "general" as three points, "more difficult, worse" as the two points, "very hard, very bad" as 1 point. We scored technology difficulty and economy indexes of the schemes, took arithmetic mean for evaluation of each expert, as shown in tableⅨ.

TABLE Ⅸ
EVALUATION INDEX OF COLUMN

Other	Technology difficulty (efficiency)	4.5	2.5	1.5	3
	Economy (efficiency)	4	3.5	2	2.8

1) Confirm reference sequence

Selecting reference sequence, according to "benefit type" index took its maximum, "cost type" index took its minimum, got the reference sequence from table Ⅱ and tableⅨ:

$X_0(k)$={6. 54, 122, 3345, 46. 22, 75. 72, 106. 72, 106. 91, 15096. 9, 2568, 4. 5, 4}

2) The static performance evaluation index

Used optimal index set E * (reference sequence $X_0(k)$) and the object of the evaluating index to form the static performance evaluation index matrix:

$$E=\begin{bmatrix} 6.54 & 122 \\ 13.42 & 204 \\ 40.03 & 173 \\ 6.54 & 122 \\ 7.82 & 136 \end{bmatrix}^T \quad (9)$$

Substitution into the type (4) and nondimensionalization, used the type (5) to calculate correlation coefficient value ti (k), and got correlation coefficient matrix:

$$T_1=\begin{bmatrix} 0.7091 & 0.6755 \\ 0.3333 & 0.7697 \\ 1 & 1 \\ 0.9290 & 0.9245 \end{bmatrix}^T \quad (10)$$

Then calculated the comprehensive evaluation results vector of B1 was

$$L_1=Q_{B1}\times T_1=(0.2857,0.7143)\times \begin{bmatrix} 0.7091 & 0.3333 & 1 & 0.9290 \\ 0.6755 & 0.7697 & 1 & 0.9245 \end{bmatrix} =(0.6851,0.6450,1,0.9258) \quad (11)$$

3) The vibration resistance evaluation index

Similarly, for vibration resistance index, we could get correlation coefficient matrix:

$$T_2=\begin{bmatrix} 0.3483 & 0.4429 & 0.3713 & 0.4397 \\ 1 & 1 & 1 & 1 \\ 0.3333 & 0.3647 & 0.5299 & 0.8052 \\ 0.41489 & 0.4529 & 0.5124 & 0.6458 \end{bmatrix}^T \quad (12)$$

Comprehensive evaluation results vector of B2 was

$$L_2=Q_{B2}\times T_2=(0.3889,0.2995,0.1881,0.1235)\times \begin{bmatrix} 0.3483 & 1 & 0.3333 & 0.4189 \\ 0.4429 & 1 & 0.3647 & 0.4529 \\ 0.3713 & 1 & 0.5299 & 0.5124 \\ 0.4397 & 1 & 0.8052 & 0.6458 \end{bmatrix} =(0.3922,1,0.4380,0.4747) \quad (13)$$

4) The lightweight evaluation index

Similarly, for lightweight index, we could get correlation coefficient matrix:

$$T_3=\begin{bmatrix} 1 & 0.9801 \\ 0.9193 & 0.9548 \\ 0.3333 & 1 \\ 0.7629 & 0.9367 \end{bmatrix}^T \quad (14)$$

Comprehensive evaluation results vector of B3 was

$$L_3=Q_{B3}\times T_3=(0.75,0.25)\times \begin{bmatrix} 1 & 0.9193 & 0.3333 & 0.7629 \\ 0.9801 & 0.9548 & 1 & 0.9367 \end{bmatrix} =(0.9950,0.9282,0.5000,0.8064) \quad (15)$$

5) Other evaluation indexes

Similarly, for other indexes, we could get correlation coefficient matrix:

$$T_4=\begin{bmatrix} 1 & 1 \\ 0.4284 & 0.7538 \\ 0.3333 & 0.4328 \\ 0.5003 & 0.5601 \end{bmatrix}^T \quad (16)$$

Comprehensive evaluation results vector of B4 was

$$L_4=Q_{B4}\times T_4=(0.75,0.25)\times \begin{bmatrix} 1 & 0.4284 & 0.3333 & 0.5003 \\ 1 & 0.7528 & 0.4328 & 0.5601 \end{bmatrix} =(1,0.5095,0.3582,0.5152) \quad (17)$$

D. The first layer of comprehensive evaluation

Used L1, L2, L3, and L4 to structure the first layer of evaluation matrix

$$L=\begin{bmatrix} 0.6851 & 0.6450 & 1 & 0.9258 \\ 0.3992 & 1 & 0.4380 & 0.4747 \\ 0.9950 & 0.9282 & 0.5000 & 0.8064 \\ 1 & 0.5095 & 0.3582 & 0.5152 \end{bmatrix} \quad (18)$$

$$R=Q_A\times L=(0.6759,0.8043,0.6378,0.6972) \quad (19)$$

E. Evaluation results

From analysis of the second layer of evaluation result vector L1, L2, L3, and L4 indicated that according to the static performance index, the third scheme was optimal; according to vibration resistance evaluation index, the second scheme was optimal; according to lightweight evaluation index, the first scheme was optimal; according to other evaluation index, the first scheme optimal. It could be found that a single index evaluation method couldn't measure comprehensively a column scheme superior or not.

From the comprehensive evaluation result vector R, the comprehensive performance of the second scheme was better than other schemes.

VI. CONCLUSION

1) The column structure of ribs with “hexagonal honeycomb” shape has the best comprehensive performance in comparison with that of “X” shape, “triangle” shape and “kagome” shape.

2) The results of research show that changing arrangement pattern for ribs of column of machine tool to honeycomb structures could improve comprehensive performance.

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3) The Gray Analytic Hierarchy Process given in the paper is effective for evaluation of comprehensive performance of machine tool.

4) Bionic design could improve the structure of gantry machine center. It was an effective and innovative method for machine tool design.

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