Research Article

Fuzzy Algorithm Based Bionic Optimization Design of Boring Machine Column

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A large-scale CNC boring machine would not be complete without a column. The tortoise shell is chosen as the bionic prototype, and the column structure is optimized using the bionic optimization design approach, using the column of a thg6920 boring machine as the research object. The structural similarity between the completed turtle shell and the boring machine column is 0.796, according to the fuzzy method. The structural optimization and topological optimization of the column imitating turtle shell are carried out with the ANSYS Workbench, and the bionic column model is established, and then the static analysis and modal analysis are carried out. After bionic optimization and topology optimization, the weight of the column is reduced from 87061 kg to 82107 kg, the maximum stress is reduced to 3.8637 MPa, the maximum stress is reduced by 28.9% compared with the original column, and the specific stiffness and specific strength are increased by 20.65% and 29.4%, respectively. The column structure has also achieved good optimization results in stiffness, strength, and stability.

1. Introduction

The science of getting computers to operate without being explicitly programmed is known as machine learning. Self-driving vehicles, realistic voice recognition, successful online search, and a much-enhanced understanding of the human genome have all been made possible by machine learning in the last decade. Machine learning is now so common that almost everyone uses it daily without even realizing it. Many academics believe it is the most effective technique to get closer to human-level AI. In ML approaches, the most interesting part is the training process of the machine which is very important. Before the training process, training data is needed to be collected and then the machine is trained on the data. Moreover, researchers are working on the development of various methodologies to ensure that after the learning process is over, a machine should be capable of mimicking human beings in some activities, especially for those which it is designed. The machine tool column is not only the key part of the whole NC boring machine, but also a large part. Whether it is the static or dynamic performance, it will directly affect various machining accuracy of the NC boring machine. Improving the specific stiffness of the column structure of the NC boring machine will help to improve the overall system dynamic performance. In recent years, many people at home and abroad have focused on this research. Chen et al. [1] analyzed the change of assembly stress of the column joint surface of the heavy gantry machine tool; Guo and Yang [2] analyzed and studied the vibration modes, natural frequencies, and maximum deformation areas of the column bed of NC machine tool with ANSYS; Yu et al. [3] studied improving the vibration resistance, stability and finishing performance of machine tool columns; Zheng [4] studied the column structure of NC milling machine; Lv et al. [5] analyzed the stress of machine tool column of vertical machining center according to the joint surface theory. Kim [6] analyzed and optimized the internal rib plate structure of the column of the multi-axis and multi-function machine tool; Guerkov et al. [7] studied and analyzed the whole machine tool; Venugopal et al. [8] found through research that the alternative materials of machine tool structure have high damping characteristics and small
Young’s modulus; Paweko et al. [9] studied and improved the accuracy of machine tool stiffness evaluation; In the same year, Aggogeri et al. [10] proposed a feedback feed active vibration controller to curb the vibration generated during machining.

In this paper, we have reported on the developmental process of the fuzzy logic-based bionic optimization design of boring machine column which has the capacity to develop new mechanical structures, shapes, and sizes that are based on the principle described for the bionic structures. The structural similarity between the completed turtle shell and the boring machine column is 0.796, according to the fuzzy method. ANSYS Workbench is used to perform the structural and topological optimization of the turtle-shell-inspired column, as well as the establishment of the bionic column model, static analysis, and modal analysis.

The rest of the manuscript is organized as given below.

In Section 2, bionic structure based on natural biology is reported that is capable of generating new structures, shapes, and sizes of the underline organism. Initially, a detailed and thorough discussion is presented on the optimization structure of the bionic structure which is followed by the structural design of the bionic structure in Section 3. In Section 4, the topology optimization of the column is reported where it is defined how an optimal topology could be obtained. Results are presented in Section 5 which is followed by the concluding remarks.

2. Bionic Structure Based on Natural Biology

Bionics is to compare, study and explain the working principles and mechanical principles of the structure and functions of organisms, and invent new mechanical structures, sizes, and shapes according to these principles, so as to design product optimization and upgrading suitable for the field of production and manufacturing. The combination of bionics and structural design can achieve the purpose of optimal design. The modern bionic design takes the overall performance or characteristics of natural animals and plants as the reference object, and selectively applies the principles of those characteristics in the design processes around a certain feature. Using the bionic method to optimize the structure is to collect the structural characteristics and functions of organisms and establish a similar model of mechanical equipment to improve and improve the performance. The purpose of establishing a similar model is to realize similar functions through structural similarity [11].

2.1. Bionic Structure Optimization Design Concept. To carry out the structural bionics, we must first select the imitated animal and plant objects, then analyze and study them according to a specific animal or plant selected, extract some features that need to be used, and combine the machinery to be optimized, so as to optimize the performance or function of the specified machinery. The link between the back and belly armour in the turtle shell is discovered to have a structure comparable to the stiffener.

As a result, a virtual model of the connecting structure is created in order to thoroughly examine its materials, properties, and functions. A number of optimization strategies are created based on this virtual model, and qualitative and quantitative analysis is performed using a computer, current technology, mathematics, and geometry. To produce a structure that fulfills the requirements of contemporary manufacturing and processing, the structural and morphological benefits of the link between the back armour and the belly armour of the turtle shell are integrated into the column structure.

3. Structural Design of Bionic Column

3.1. Research on Characteristics of Bionic Prototype. By observing the macrostructure of the turtle shell, Figure 1 can be seen that the turtle shell is approximately flat, mainly composed of back armor and abdominal armor. The whole is also thin, and there is a large cavity space inside. The back armour of tortoise shell is often in the shape of an arch bridge. The back armour of some tortoise shells is more curved, and some even appear spherical. The ribs, spine, and sternum of a turtle are different from those of common animals. They are combined with the back or abdomen of the turtle shell. The connection between the back armor and the abdominal armor also has a structure similar to the stiffener. The structure of the connection mainly plays the role of support and connection. At the same time, the abdominal armor is linear, which is very similar to the overall structure of the column. This structure is studied and applied to the column structure, to achieve the purpose of bionic optimization.

The turtle shell possesses structural properties such as low weight, better strength, and stiffness, stronger bending resistance, and so on, because of tens of thousands of years of evolution and natural selection. As a result, this study focuses on improving the column structure’s bending performance, light-specific gravity, high strength, and high rigidity.

3.2. Similarity Analysis Based on Fuzzy Algorithm. The fuzzy method from the fuzzy evaluation standard is used to calculate the similarity of many attributes between the column and the turtle shell. There are certain similarities between bionics or bionic structures and the study item is recorded as $Q_0$, or similarity for short, in the similarity hypothesis. The similarity is defined as the arithmetic mean ratio of various attributes shared by the two elements, with a value larger than zero but less than one. The higher the score, the more similar some qualities of the two things are; on the other hand, the lower the value, the larger the difference in some characteristics between the two objects. The characteristics of a biological or biological structure and the research object involved in the evaluation are recorded as similarity elements $\delta I$ (each feature is counted as a similarity element), and the number of features participating in the evaluation is recorded as $N$, then the formula for calculating the similarity is as follows:
\[ Q = \sum_{i=1}^{n} \left[ \sigma_1 q(\delta_i) + \sigma_2 q(\delta_2) + \sigma_3 q(\delta_3) + \cdots + \sigma_n q(\delta_n) \right] = \sum_{i=1}^{n} \sigma_i q(\delta_i), \] (1)

of which

\( Q \) is the similarity \((0 < Q < 1)\);

\( \mu_i \) is the weight coefficient \((0 < \sigma_0 < 1 \text{ and } \sum_{i=1}^{n} \sigma_i = 1)\);

\( \beta_i \) is the similarity vector of similar elements;

\( \delta_i, \) the values of I form a set \( U = \{ \text{structure, function, size, load, constraint} \ldots \} = \{ \delta_1, \delta_2, \delta_3, \ldots, \delta_n \}; \)

\( \delta_i \epsilon U, \ i = 1, 2, 3, \ldots, n, \) then \( \delta_{ij} \) represents the relative importance of \( \delta_i \) to \( \delta_j, \) so the expression of judgment matrix \( D \) can be obtained as follows:

\[
D = (\delta_{ij})_{n \times n} = \begin{bmatrix}
\delta_{11} & \delta_{12} & \cdots & \delta_{1j} & \cdots & \delta_{1n} \\
\delta_{21} & \delta_{22} & \cdots & \delta_{2j} & \cdots & \delta_{2n} \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\delta_{i1} & \delta_{i2} & \cdots & \delta_{ij} & \cdots & \delta_{in} \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\delta_{n1} & \delta_{n2} & \cdots & \delta_{nj} & \cdots & \delta_{nn}
\end{bmatrix},
\] (2)

\[
\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{\delta_{ij} \sigma_j}{\sigma_i}
\]

Calculated by \( \sigma = (0.42, 0.25, 0.2, 0.25)^T \), \( \lambda_{\max} = 4.1752 \).

\[
r_{ij} = \frac{\min(U_{ij}(A_j), U_{ij}(B_j))}{\max(U_{ij}(A_j), U_{ij}(B_j))},
\] (3)

\[
CR = \frac{CI}{RI}
\] (4)

In the formula,

\( CR \) is the random consistency ratio;

\( CI \) is the consistency index;

\( RI \) is the random average consistency index.

(1) Here, \( U_{ij}(A_j) \) and \( U_{ij}(B_j) \) are determined by the consistency ratio CR, and \( CR = CI/RI. \) RI is calculated by formula (4) and checked in Table 1. The value of RI is 0.8931. CR = 0.065 < 0.1, so the selection is reasonable. According to the calculation results, identify the similarity between the elements of the column and the turtle shell prototype, record the similarity of similar elements \( q(\delta_i) = (0.8, 0.6, \ldots). \)

0.8, 0.6). To sum up, the value of similarity \( Q \) is obtained:

\[
Q = 0.42 \times 0.8 + 0.25 \times 0.6 + 0.2 \times 0.8 + 0.25 \times 0.6 = 0.796.
\] (5)

The value of similarity \( Q = 0.796, \) that is, the similarity between tortoise shell and boring machine column is 79.6%, and the similarity between them is large. Therefore, a tortoise shell as a bionic prototype of a boring machine column is desirable.

3.3. Establishment of Bionic Column Model. After reasonable evolution and several experiments, the transverse rib plate is combined around the inner wall of the column, and the specific size parameters are set. The drawn results of the transverse bionic rib plate are shown in Figure 2. Draw the thickness and proper radius of the turtle shell back armor, bend the vertical rib plate in sections and small radians, and set the specific size parameters, then the drawn results of the vertical bionic curved rib plate are shown in Figure 3:

The experimental research shows that the more the number of transverse stiffeners in the column, the smaller the deflection ratio of the column and tends to be close to 0.9. However, when the number of transverse stiffeners is equal to 10, the deflection is more appropriate. At this time, the stiffness of the column reaches its best when the mass utilization rate is the highest. Therefore, tensile modeling and array replication are carried out according to the above design drawings to establish 10 transverse stiffener plates, and square stiffener plates with a section of 100 × 50 mm are welded near the inner wall surface of the contact guide rail and the end face of the vertical curved stiffener plate [12]. After orderly arrangement and combination, a complete stiffener frame is finally formed, as shown in Figure 4 below.

4. Topology Optimization of Column

The physical layout of the column is defined as the topology which is one of the most vital factors and has a key role in the bionic structure. A detailed discussion on this is presented here which is divided into subsections for easy follow-up and understandability.

4.1. Modeling of Topological Column. Based on the fact that it does not affect the performance of the bionic column, model it according to the above topological optimization results,
and then repeat the operation steps consistent with the modal and static analysis of the column prototype, define the same material, set the same load and constraint conditions, mesh the bionic column model after topological optimization, and finally obtain the three-dimensional modeling and mesh model of the bionic column model after topological optimization, as shown in Figures 5 and 6 respectively:

After material definition and meshing, the structural mass of the topological bionic column is 82107 kg, the number of nodes is 706361 and the number of elements is 166839. Compared with the prototype column, the mass of the topological column is reduced by 4954 kg, which reduces the overall mass of the column. To verify that the excellent performance of the bionic column after topology optimization remains unchanged, it is also necessary to conduct modal and static analysis and comparison between the topological column and the original column model.

4.2. Finite Element Analysis of Bionic Column and Topology Optimization Bionic Column. For the modal analysis of the column optimization model of the tortoise shell structure, similarly, the bionic column is also subject to the condition constraints consistent with the original column model, that is, the bottom end face is set as the fixed constraint. Through the modal analysis of ANSYS Workbench, the sixth-order vibration modes of the bionic column model are shown in Figures 7(a)–7(f).

The bionic column is set with the same mechanical conditions as the column prototype. After setting constraints and loads, the deformation distribution of the bionic column is analyzed as shown in Figure 8. The maximum displacement of the bionic column is analyzed and the harmonic response is analyzed at the same time. The stress distribution of the bionic column is obtained under the same loads and constraints as the column prototype, as shown in Figure 9. By observing and comparing the stress nephogram of the two, it can be seen that the maximum stress of the bionic optimized column is 4.2486 MPa, which is 1.185 MPa less than that of the original column, and the overall stress of the bionic column is small:

The modal analysis of the bionic column after topology optimization is consistent with the constraint conditions of the column prototype. The bottom end face is set as a fixed
constraint, and the solution results and corresponding images are obtained by the workbench finite element platform. After analyzing and deriving the image in the finite element, the sixth order vibration mode of the topological bionic column model is obtained, as shown in Figures 10(a)–10(e).

Under the Same Load and Constraint Conditions, the Displacement and Stress of the Bionic Column after Topology Optimization are Analyzed. The Analysis Results are shown in Figures 11 and 12.

4.3. Comparative Analysis of Bionic Column and Topology Optimization Bionic Column. The optimization results obtained through multiple comparative analysis and simulation optimization are sorted and summarized. The performance analysis results of column prototype and topological column are summarized in Table 2.

Based on the comparison of the above data summary results, the bionic column and column prototype after topology optimization are analyzed and summarized, and the final optimization results are as follows:

(1) Statics: the maximum stress of the bionic column after topology optimization is reduced to 3.8637 MPa, which is 28.9% lower than that of the original column. The maximum displacement is reduced to 0.126 mm, which is 22.1% lower than the original column.
In terms of quality: compared with the prototype of the column, the mass of the bionic column after topology optimization is reduced by 4954 kg, a year-on-year decrease of 5.7%.

In terms of mode: in the sixth order vibration mode of the bionic column after topology optimization, compared with the original column model, the first, second, third, and sixth orders are greatly improved, with a year-on-year increase of 10.9%, 15.9%, 33.2%, and 12.3% respectively.

In terms of specific strength, the bionic column after topology optimization is 48.4% higher than the column prototype.
Figure 6: Mesh model of topological bionic column.
Figure 7: Sixth order modal analysis diagram of bionic column (from first order to sixth order).

Figure 8: Cloud diagram of maximum displacement of bionic column.

Figure 9: Cloud diagram of maximum stress of bionic column.
Figure 10: Sixth order modal analysis diagram of bionic topological column (first order to sixth order in order).

Figure 11: Cloud diagram of maximum displacement.

Figure 12: Cloud diagram of maximum stress of topological bionic column.
Table 2: Summary of topology optimization data results.

| Performance parameter | Column prototype | Topology optimization column | Optimization change rate (%) |
|------------------------|------------------|-----------------------------|-----------------------------|
| Maximum stress (MPa)   | 5.434            | 3.864                       | −28.9%                      |
| Maximum deformation (mm)| 0.162            | 0.126                       | −22.1%                      |
| Overall quality (kg)   | 87061            | 82107                       | −5.7%                       |
| First order mode (Hz)  | 21.6             | 23.96                       | +10.9%                      |
| Second order mode (Hz) | 22.37            | 25.93                       | +15.9%                      |
| Third order mode (Hz)  | 35.81            | 47.7                        | +33.2%                      |
| Fourth order mode (Hz) | 54.12            | 57.23                       | +5.75%                      |
| Fifth order mode (Hz)  | 61.64            | 62.03                       | +0.6                        |
| Sixth order mode (Hz)  | 63.17            | 70.96                       | +12.3%                      |
| Specific strength (N·m/kg) | 0.00275       | 0.0041                       | +48.4%                      |
| Specific stiffness [MPa/(kg:mm)] | 0.92         | 1.255                       | +36.4%                      |

(5) In terms of specific stiffness, the bionic column after topology optimization is 36.4% higher than the column prototype.

5. Conclusion

Compared with the original column model, the stress, deformation, and mass of the tortoise shell column model after topology optimization are significantly reduced, and the specific strength and specific stiffness are significantly improved. The bionic column optimized by imitating the structural characteristics of the turtle shell improves its structural parameters and performance globally, especially in terms of lightweight, stability, and deformation resistance. In terms of processing technology, the welding scale of the rib plate is reduced, and the overall quality of the column is reduced, which is conducive to the improvement of material utilization and market competitiveness. After topology optimization and bionic optimization, the column has better characteristics, a more stable structure, and a lighter weight. The parameters of the column of the 6920 ram mobile floor milling and boring machine are extracted and a three-dimensional model is established. The similarity between the column and the turtle shell is calculated by using the basis of bionics and mathematical fuzzy similarity theory. The column and the turtle shell have a similarity of 0.796, indicating that bionic optimization of the column is possible. The maximum deformation is 15.7 percent lower than that of the original column, and the maximum stress value is 21.8 percent lower than that of the original column, according to study and comparison of modal sixth order natural frequency and static stress-strain of the column and bionic column. The natural frequencies of the first three steps have increased by 8.2 percent, 5.9 percent, and 19 percent, respectively, while the natural frequencies of the last three steps have only slightly improved; the specific stiffness and specific strength have increased by 20.65 percent and 29.4 percent, respectively, when compared to the original column. The structural performance may be considerably improved via bionic optimization. Then, the mass of the bionic column is topologically optimized to reduce the mass of the boring machine column by 4954 kg, which is 5.7% lower than the original column. At the same time, the natural frequency, specific stiffness, and specific strength of the first three and sixth modes are further increased.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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