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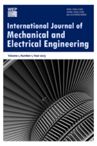

Biomimetic Optimization of Machine Tool Columns Based on Leaf Sequence Structures

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ABSTRACT

With the goal of enhancing the overall performance of the column, which is one of the key components of the machine tool, a biomimetic design approach was employed in this study. Drawing inspiration from the leaf arrangement structure found in nature, the internal supporting structure of the column was designed using principles and methods of structural biomimicry. Subsequently, finite element static analysis was conducted on the biomimetic column structure. Sensitivity analysis of the optimized pillar structure dimensions was performed, resulting in a comprehensive design solution with superior performance. Following optimization, the mass of the column was reduced by 55.39 kg, representing a decrease of 2.7%; maximum deformation decreased by 0.0738 mm, reducing by 35.18%; maximum equivalent stress decreased by 0.44 MPa, a reduction of 5.4%; and the first-order natural frequency increased by 12.43 Hz, rising by 22.91%. Through effective optimization, while ensuring rigidity, the static and anti-vibration performance of the beam were improved, facilitating lightweight design.

KEYWORDS

Column; Biomimetic Design; Sensitivity Analysis; Lightweight Design; Optimization Design.

1. INTRODUCTION

As the "mother machine" of industry, the technological level of CNC machine tools directly determines the advanced level of manufacturing processes. Currently, China's machine tool industry is in an important stage of transformation and upgrading, where domestic machine tools must break through technological bottlenecks such as high speed, high efficiency, and high precision[1]. Biomimetic optimization design of machine tool structures aims to study the structural characteristics and functional principles of organisms, and apply their excellent structural forms to engineering to achieve the desired design effects[2]. Currently, drawing inspiration from the shapes and internal features of animals and plants in nature to design mechanical structures has become an important component of the field of structural biomimicry. Many scholars at home and abroad have applied the theory of structural biomimicry to improve the design of various components of machine tools. For example, Zhao Ling et al. improved the layout of ribs by analyzing the vein structure of lotus leaves, thereby enhancing the overall structural efficiency of the beam[3]. Gao Hanjun et al. imitated the structure of the human cervical vertebrae to optimize the design of the machine tool's spindle sleeve, thereby enhancing the rigidity and overall performance of the sleeve[4]. Ding Xiaohong et al. utilized the growth morphology and formation mechanism of plant root systems to optimize the design of reinforced thin-shell structures[5]. Scholars such as Mattheck and Baumgartner, based on the principle of constant stress in plant growth, have designed new biomimetic structures[6-7]. Neugebauer et al., based on principles of biomechanics, have redesigned the motion guide rail structure of machine tools, improving the overall stability and motion accuracy of the machine tools[8]. Zhang et al. used honeycomb sandwich structures as a biological reference to perform biomimetic design on the transverse column of machine tools, enhancing the positioning accuracy of the column[9].

By observing the way plants endure forces, similarities were found between the stress and constraint patterns of plant leaves and machine tool columns, prompting the biomimetic design of the latter, which serves as a crucial supporting component of machine tools. Focusing on CNC machine tool columns, this study initially conducted three-dimensional modeling of the columns' original models, followed by finite element analysis using relevant software. Subsequently, biomimetic design was applied to the columns, and static analysis was performed on the biomimetically designed columns. A comparison was made between the biomimetic designs and the original models, revealing that the biomimetic optimization design resulted in a certain improvement in the static performance of the designed columns.

2. FINITE ELEMENT ANALYSIS (FEA) OF THE ORIGINAL MACHINE TOOL COLUMN

2.1. Static Analysis of the Column

The main components of CNC machine tools include the bed, worktable, column, beam, and spindle box. The column analyzed in this paper is a column of a certain CNC gantry machine tool. During operation, it needs to accommodate the Z-axis movement of the beam and the spindle box, and its rigidity directly affects the machining accuracy of the machine tool. The material of the column is HT300, with corresponding parameters: density of 7300 kg/m^3, elastic modulus of 148000 MPa, and Poisson's ratio of 0.27. The loads on the column mainly include its own weight, the weight of the beam, spindle box, and the connecting beams, as well as the cutting forces during machining. The bottom of the column is connected to the bed with bolts. Finite element analysis was conducted at the position where the beam reaches the farthest end and the sleeve extends the longest, resulting in the finite element model of the original column as shown in the figure.

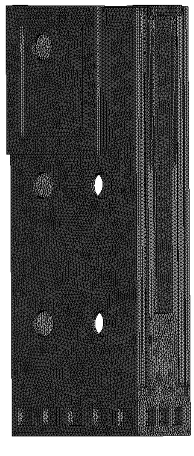


Fig 1. Finite element model of the original column

The analysis revealed that the maximum deformation of the original column is 20.984μm, and the maximum equivalent stress is 8.156 MPa.

2.2. Modal Analysis of the Column

When conducting modal analysis on the original column, the boundary conditions are set consistent with those used in static analysis. Higher-order modes have minimal influence on vibration, while lower-order modes are more prone to resonance. The results of the first six modal modes are as follows:

Table 1. First six Modal modes of the original column

Mode	Natural Frequency /Hz
1	54.26
2	86.10
3	178.78
4	220.01
5	324.51
6	335.21

3. MECHANICAL ANALYSIS OF PHYLLOTAXIS STRUCTURE

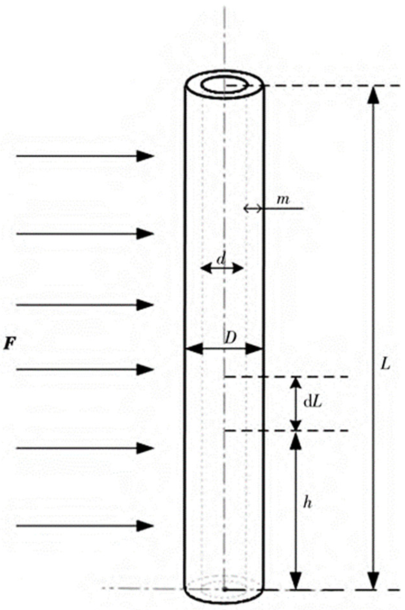
"Phyllotaxis" refers to the arrangement or order of leaves on a plant stem. It describes the position and arrangement of leaves relative to the stem. Some common phyllotaxis patterns include opposite (opposite phyllotaxis), spiral (spiral phyllotaxis), alternate (alternate phyllotaxis), and whorled (whorled phyllotaxis). This paper mainly draws inspiration from opposite and whorled phyllotaxis in plants. Specifically, opposite phyllotaxis refers to the growth of two leaves in opposite directions at each node of the plant stem, while whorled phyllotaxis refers to the growth of three or more leaves at each node of the plant stem.

A plant stem typically consists of the main stem (or stem) and various levels of branches. Plant stems are often hollow structures, similar to hollow cylinders. Macroscopically, plant stems have a hollow structure, resembling a cantilever beam fixed at the bottom. In their natural state, they bear bending moments, shear forces, and torsional moments caused by wind loads, self-weight, etc., demonstrating strong bending resistance. This structural and mechanical similarity is observed in machine tool columns, which are also hollow, fixed at the bottom, and subjected to bending and torsional loads, as depicted in the diagram below:

(a)Opposite phyllotaxis (b)Whorled phyllotaxis

Fig 2. Phyllotaxis Structure Diagram

The phyllotaxis structure of a plant mainly consists of a main stem and lateral branches. When performing biomimetic optimization design of machine tool columns based on phyllotaxis structure, the design of the main stem and the arrangement of lateral branches are crucial for evaluating the column. Let the wall thickness of the plant stem be represented as m, the outer diameter as D, the inner diameter as d, and the ratio of inner to outer diameter as α. The ratio of wall thickness to outer diameter is defined as the wall thickness ratio μ, that is, μ = m/D. Assuming the wind load on the plant within a height range of L is a constant value F, the stress analysis of the plant main stem is conducted. The stress is illustrated in the figure below:



Note: *dL* represents the differential length element at the height of the phyllotaxis.

Fig 3. Stress diagram of the phyllotaxis main stem

According to the theory of material mechanics bending strength, the bending moment of the main stem of the phyllotaxis structure at a height of h is:

$$M=\int_0^L FdL\approx\frac{F}{2}(L-h)^2 \tag{1}$$

The sectional modulus of the plant stem is:

$$W=\frac{1}{32}\pi D^3\left(1-\alpha^4\right) \tag{2}$$

Assuming there is a solid cylindrical structure with the same outer diameter as an empty cylindrical structure, which is , its sectional modulus is:

$$W_1=\frac{1}{32}\pi D_1^3 \tag{3}$$

The ratio of the sectional modulus of the solid stem to that of the hollow stem is:

$$\frac{W}{W_1}=\frac{1+\alpha^2}{1-\alpha^2}>1 \tag{4}$$

From formula (4), it can be inferred that the bending strength of a hollow plant stem is greater than that of a solid stem with the same outer diameter, and it is influenced by the ratio of outer diameters.

4. BIOMIMETIC STRUCTURAL DESIGN AND FINITE ELEMENT ANALYSIS OF THE COLUMN

4.1. Biomimetic Design of the Column

The original internal reinforcement of the column structure is simple, consisting of a cross-shaped reinforcement plate. When optimizing the column structure using biomimicry, the internal reinforcement plates of the column are redesigned based on the phyllotaxis structure. During the biomimetic design of the internal structure of the column, the plant stem is simplified as a hollow cylinder serving as the support part of the column, while the leaves are simplified as rectangular reinforcement plates extending from the hollow cylindrical body. When subjected to external forces, the opposite phyllotaxis structure ensures uniform stress distribution and structural stability. Two biomimetic column structures based on opposite phyllotaxis are designed accordingly. In the case of whorled phyllotaxis, four reinforcing ribs are designed at the stem nodes to ensure uniform stress distribution. The biomimetic column structures described above are illustrated in the following figure:

(a)Opposite Type 1 (b)Opposite Type 2 (c)Whorled Type

Fig 4. Biomimetic column structure diagram

4.2. Finite Element Analysis of the Biomimetic Column

Finite element analysis was conducted on the aforementioned biomimetic column to examine the influence of the biomimetic structure on its static and dynamic performance. The material, load, and constraint settings chosen for finite element analysis were consistent with those of the original structure column. The finite element results of the biomimetic column are shown in the table below:

Table 2. Simulation results of the biomimetic column

Column Structure	Mass/kg	Maximum deformation /μm	Maximum equivalent stress /MPa	First-order natural frequency /Hz
Opposite Type 1	1966	14.193	8.326	66.62
Opposite Type 2	2002	14.271	8.328	66.15
Whorled Type	2010	14.931	8.249	64.152

Based on Table 2, it is observed that the finite element results of the biomimetic structure column show improvements compared to the original column structure. After analysis, it is found that Opposite Type 1 has the smallest mass, with the second lowest maximum deformation but a very small difference, and the maximum equivalent stress is similar among the three options and far below the allowable stress. Option 1 has the highest first-order natural frequency. Therefore, Opposite Type 1 is selected for further optimization.

5. OPTIMIZED DESIGN OF THE BIOMIMETIC COLUMN STRUCTURE

Based on the finite element analysis of the biomimetic columns in the previous chapter, the simulation results of the three column types have been obtained, and the optimization plan for the columns has been determined. Since there is still room for further improvement in the static performance of Opposite Type 1 column, the following section identifies the dimensional parameters that have a significant impact on the maximum deformation, maximum equivalent stress, and first-order natural frequency of the column. Additionally, the influence of the column's own weight on deformation cannot be ignored, so it is necessary to minimize the mass of the column as much as possible.

5.1. Dimensional Sensitivity Analysis

Based on the analysis of the determined biomimetic column design characteristics, the following 8 key dimensions are preliminarily identified as input parameters for sensitivity analysis, as shown in the figure below: inner diameter of the support beam P1, thickness of the released reinforcement P2, length of the biomimetic reinforcement P3, outer diameter of the support beam P4, diameter of the side opening P5, left wall thickness P6, right wall thickness P7, and back wall thickness P8. As illustrated in the figure below.

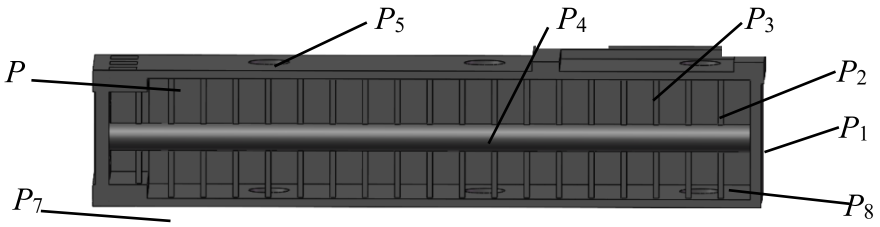


Fig 5. Selection of key dimensions for the column

After parameterizing the above 8 dimensions, the column mass, maximum deformation, and first-order natural frequency are selected as three output functions to establish a multi-objective function relationship with the 8 key dimensions. Due to the large number of input parameters, 80 sample points are set. The parameter ranges are automatically set using the parameter correlation module and then adjusted accordingly. Subsequently, a dimensional sensitivity analysis is conducted to determine the sensitivity of the output parameters to the input parameters, as shown in the figure below:

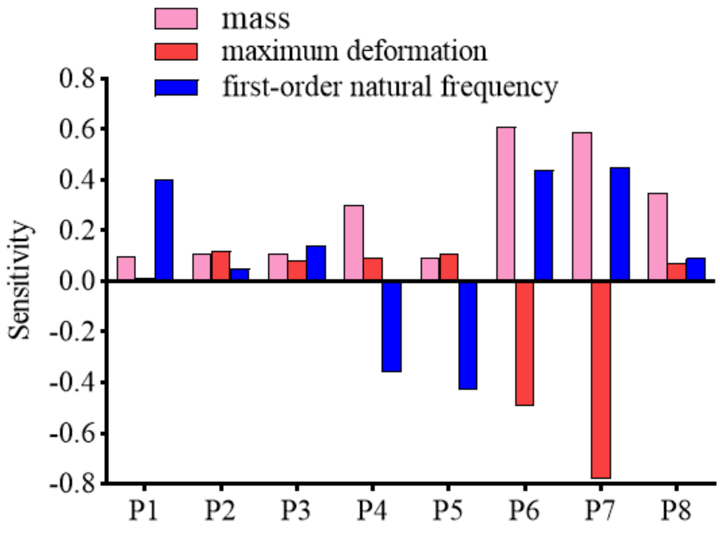


Fig 6. Sensitivity analysis of key dimensions for the column

From the above figure, it can be observed that the sensitivity values are both positive and negative. A positive sensitivity indicates that an increase in the input parameter leads to an increase in the output parameter, while a negative sensitivity indicates that an increase in the input parameter results in a decrease in the output parameter. The positive or negative sign of sensitivity does not indicate its magnitude; rather, it indicates a positive or negative correlation. The magnitude of sensitivity refers to the absolute value of its value [10-11]

Through the sensitivity analysis of key design dimensions of the column, it was found that parameters P1, P2, and P3 have relatively small effects on the output parameters compared to other parameters.

Therefore, they are disregarded in subsequent optimizations. Consequently, parameters P4, P5, P6, P7, and P8, which exhibit higher sensitivity to the optimization objeBased on the sensitivity analysis of the column structure design dimensions and relevant column structure design data, after generating design dimensions in response surface optimization using finite element analysis software, the corresponding values are modified to a certain extent. The final range of dimension values for the column to be optimized is shown in the table below:

Table 3. Range of values for the column dimensions to be optimized

parameters	initial values(mm)	range of values(mm)
P_4	100	100~120
P_5	150	150~180
P_6	30	25~35
P_7	30	25~35
P_8	30	25~35

5.2. Analysis of Size Optimization Results

Based on the column's design dimensions and their ranges determined earlier, during the optimization process, the importance levels of "mass," "maximum deformation," and "first-order natural frequency" are set to default. Subsequently, to ensure that the optimized results are not inferior to the pre-optimized ones, constraints are applied to each optimization objective. Considering that the design points of the optimization candidates are calculated and fitted by finite element software, it is difficult to achieve the dimensional accuracy in actual production and processing. Therefore, the optimized results need to be rounded, and the rounded results are then incorporated into the column structure calculation. The results are shown in the table below:

Table 4. Rounded results of column design dimensions

parameters	optimized values (mm)	rounded dimensions (mm)
P_4	100.91	100
P_5	150.29	150
P_6	29	30
P_7	34.95	35
P_8	25.43	25

Based on the rounding results in Table 5, modify the three-dimensional model of the column and conduct the corresponding finite element static analysis. The analysis results are shown in the figure below:

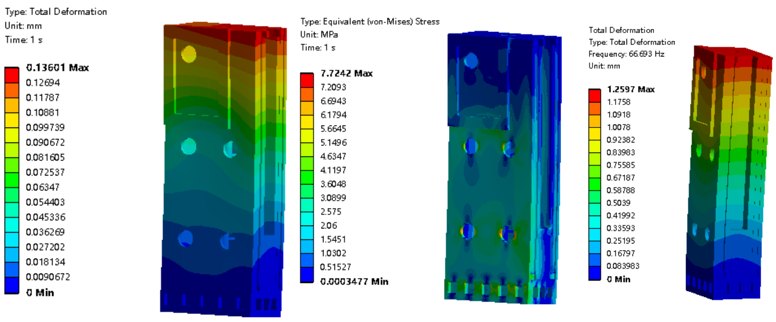


Fig 7. Finite element analysis results of column dimension optimization

Compare the final biomimetic optimization results of the column with the original column scheme finite element results, as shown in the table below:

Table 5. Comparison of static and dynamic analysis before and after column dimension optimization

Optimization Objectives	Original Scheme	After Optimization	Change
mass/kg	2051.5	1996.11	-55.39
Maximum deformation /mm	0.2098	0.1360	-0.0738
Maximum equivalent stress /MPa	8.16	7.72	-0.44
First-order natural frequency /Hz	54.26	66.69	+12.43

From the table above, it can be seen that through optimization design of the key dimensions selected from the preferred design scheme of the column, the column's mass decreased by 55.39kg, a reduction of 2.7%; the maximum deformation decreased by 0.0738mm, a decrease of 35.18%; the maximum equivalent stress decreased by 0.44MPa, a decrease of 5.4%; and the first-order natural frequency increased by 12.43Hz, an increase of 22.91%. Both mechanical performance and vibration resistance performance have been improved to a certain extent.

6. CONCLUSION

This study focuses on the column of a certain dynamic beam CNC gantry machine tool, adopting the biomimetic forms of two types of leaf sequence structures found in nature: opposite and whorled. Based on the structural and mechanical requirements of the column, biomimetic designs were applied, resulting in three biomimetic column structures. Through finite element analysis of these three biomimetic column structures, it was found that compared to the original column structure, all three biomimetic column structures exhibited improvements in both static and dynamic performance to varying degrees. Among them, the improvement in dynamic and static performance was highest for the Opposite Type 1 biomimetic column structure.

Subsequently, the Opposite Type 1 biomimetic column was further optimized through sensitivity analysis and rounding of the column structure design dimensions based on actual production values. This led to the final specific design dimensions of the column. By adopting the biomimetic column structure based on the opposite leaf sequence, the column achieved a reduction in mass by 2.7%, a decrease in maximum deformation by 35.18%, a reduction in maximum stress by 5.4%, and an increase in the first-order natural frequency by 22.91%.

Through optimization design, the column achieved lightweighting and effectively improved its static and dynamic performance, providing valuable reference for the optimization design of key components of machine tools.

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