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Research Article

Bionic Optimization Design of Rotary Tiller Based on Fuzzy Algorithm

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In order to increase the structural performance of rotary tillage knife, a badger claw toe was selected as the bionic prototype of the rotary tillage knife, and the bionic optimization design of the rotary tillage knife was carried out. The structural similarity between the badger's claw toe and the rotary tiller is 0.7073 by the fuzzy algorithm, and the shape goodness of fit between the final mole's claw toe and the digging shovel is 0.9556 by MATLAB. Using 3D modeling software NX10.0, we established a three-dimensional model of the rotary tillage knife. Furthermore, we use Workbench to carry out static analysis on the three rotary tillage knives and obtain their stress and deformation. Similarly, we also obtain their vibration frequency through modal analysis, summarize, and compare the experimental data. The outcomes indicate that compared with the ordinary rotary tillage knife, the strain and stress of the bionic rotary tillage knife with sawtooth tangent blade arrangement are reduced by 5.20% and 2.84%, respectively. Moreover, the specific strength and specific stiffness are increased by 3.99% and 6.49%, respectively. The structural efficiency is improved by 11.36%. However, the stress of the bionic rotary tiller with full serration is reduced by 7.38%. We also observed that the specific strength and specific stiffness were improved by 11.97% and 2.37%, correspondingly. Overall, structural efficiency has increased by 14.64%. The rotary tiller has also attained noble optimization outcomes in terms of stability, strength, and stiffness.

1. Introduction

Tillage machines are the main and basic part of agricultural mechanization. It has played an active role in the transformation from Chinese traditional agriculture to modern agriculture. The tillage machine with high operation efficiency, multiple functions, and improving tillage storage and moisture retention capacity has become the main research direction of new agricultural machinery in various countries, and the rotary tillage knife is one of the leading and fundamental research directions of agricultural mechanization in China. The size and structure of the rotary tillage knife are an important factor for the increase in resistance and energy consumption. The rotary tiller is an important part of the rotary tiller and also a vulnerable part. Due to the changing working environment, its average working life is about 80 h [1]. One of the problems to be solved in the research of agricultural mechanization in China is to improve the working life of rotary tillage knives, improve farming quality, and optimize the structural rationality of rotary tillage knives.

Bionics of biological structure is an important direction of bionic optimization design. Through the analysis of biological structure, we can understand the characteristics of biological structure and then integrate its characteristics into the design to make its structure more flexible and reliable, so as to enhance the performance of products. In order to increase the structural performance of the rotary tillage knife, the badger claw toe was selected as the bionic prototype of the rotary tillage knife, and the bionic optimization design of the rotary tillage knife was carried out. Through the research and analysis of the functional and structural characteristics of the badger's claw toe, taking the badger's claw toe as the bionic prototype, the IT245 rotary blade is optimized. The structural characteristics of the badger's claw toe are applied to the blade part of the rotary blade, and the optimized bionic rotary blade is obtained, which improves the sliding cutting effect of the blade, straw, and weeds.

Through finite element static analysis and modal analysis, the experimental results show that the weight reduction, stress, and deformation of bionic rotary tillage knives are improved compared with ordinary rotary tillage knives. Through the calculation and analysis of mechanical properties, it is concluded that the specific stiffness, specific strength, and specific structural efficiency of the two bionic rotary tillage knives have also been improved. Improving the performance of rotary tillers is an important link to improving production efficiency.

(i) In this paper, our aim is to improve the structural performance of the rotary tillage knife, for which the badger claw toe was selected as the bionic prototype of the rotary tillage knife, and the bionic optimization design of the rotary tillage knife was carried out.

(ii) In the second phase, using 3D modeling software NX10.0, we established a three-dimensional model of the rotary tillage knife and used Workbench to carry out static analysis on the three rotary tillage knives.

(iii) Through experimental analysis, we obtained their stress and deformation, obtained their vibration frequency through modal analysis, and summarized and compared the experimental data.

The remaining of the paper is systematized in the following fashion. In Section 2, we deliberate on bionics based on natural organisms. In Section 3, we deliberate the bionic design of the rotary tillage knife in more detail. In Section 4, we carried out the optimization analysis of the bionic rotary tiller. Note that we use the recognized fuzzy algorithm for optimization purposes. In Section 5, we discuss the obtained results and summarize our observations. In the last Section 6, the paper is concluded.

2. Bionics Based on Natural Organisms

Improving the performance of the rotary tillers is an important step towards improving production efficiency. Haijie [2, 3] designed a wedge drag-reducing rotary tiller based on the mechanical cutting model. The average torque and average power consumption of the optimized rotary tiller are 7.65% and 7.87% lower than those of the national standard rotary tiller, respectively. Jianjun et al. [4] studied the structural form and main technical characteristics of rotary tillage tools at the present stage, optimized and technically analyzed the functional structure of rotary tillage tools, and improved the operation efficiency and effect of microtillage machines. The experiment shows that the horizontal resistance, vertical resistance, and average torque of the bionic rotary tillage knife are lower than those of the national standard rotary tillage knife [5]. After the optimization of the rotary tiller, the shaft torque and amplitude of the rotary tiller are diminished by a factor of 7% and 8%, correspondingly. Furthermore, the wear rate of the rotary tiller is reduced by 10% [6]. The improved blade has a positive impact on the growth of crops. A group of 15 cm high rice straw top anchors showed that the seed germination rate of wheat and maize increased by 95.89% and 78.65%, respectively [7]. Rajesh [6] pointed out that blade shape, forward speed, and rotation speed are the key considerations to decide the status of soil crushing.

Bionics of biological structure is an important direction of bionic optimization design. Through the analysis of biological structure, we can understand the characteristics of biological structure and then integrate its characteristics into the design to make its structure more flexible and reliable, so as to enhance the performance of products. Morphological bionics is essentially the imitation and redesign of original organisms [8]. Many aircraft take birds as morphological bionic objects to design bionic machines. Through the structural bionics of mollusks, the soft robot has the advantages of high structural flexibility, strong environmental adaptability, and continuous deformation and can realize high-level environmental operation and space exploration tasks [9–12]; Based on the structural characteristics of caterpillars, Rieffel et al. [13] designed a tensioning mobile robot to realize the function of creeping, bending, and crawling.

3. Bionic Design of Rotary Tillage Knife

3.1. Characteristics of Bionic Prototype. The badger has a high efficiency in digging holes. Through the study of its claw toes, it can be found that the front and rear toes of the badger are black and brown, and both have long and powerful claws, especially the front claws. During excavation, the front claw quickly breaks the solid ground and scoops it under the abdomen and then uses the rear claw to crush the gravel and soil behind it [14]. Its front and rear legs are combined with curved claw toes so that it can dig the soil faster than other cave creatures. The inner and outer contours of the badger's claw toes are composed of two smooth curves, and the toe tips are circular, which can promote the ability to penetrate the ground [15]. As shown in Figure 1, as is the length of the toe, that is, the distance from the tip of the toe to the root of the toe. The range of A is 21 ~ 26 mm, and B is the width of the root of the toe, which is 6 ~ 7 mm. Therefore, the range of A/B is about 3 ~ 4.3.

3.2. Similarity Analysis Established on the Fuzzy Algorithm. In order to analyze the similarity between the rotary tiller and the badger's claw toe, the similarity theory in the fuzzy evaluation standard is cited for verification. The similarity between the biological prototype and engineering structure is documented as given by equation (1), and the value range of Q is $(0 < < 1)$. This means that the greater the similarity, the closer the similarity between them, and vice versa [16]. The similarity element is recorded as the similarity characteristic points amongst the engineering structures and the bionic structure prototypes are documented, and subsequently, the similarity element is striking at every characteristic point. Therefore, the similarity can be mathematically illustrated by the following equation:

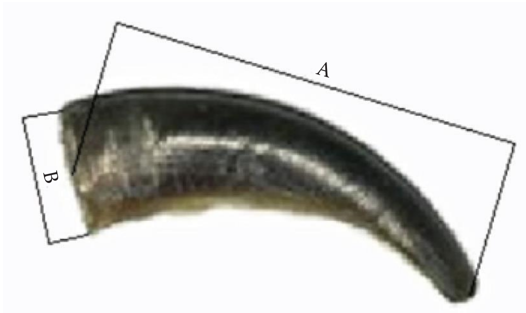


Figure 1: The badger claw toe.

$$Q = \sum_{i-1}^{n} (\beta_1 q(u_1) + \beta_2 q(u_2) + \cdots + \beta_n q(u_n)) = \sum_{i-1}^{n} \beta_i q(u_i), \quad (1)$$

where Q characterizes the similarity such that $0 < Q < 1$ is the similarity function of similar elements and denotes the weight coefficient of similar elements such that $0 \le \beta_i \le 1; \sum_{i=1}^{n} \beta_i = 1$.

This should be noted that the evaluation factor is composed of many similar elements in different aspects, and the set of each sub-factor of the evaluation factor can be composed of $U = \{u_1 + u_2 + u_3 + u_4 + \cdots + u_n\}$ = {structure, function, load, and constraint ...}. To show the judge the scale/calibration table of the matrix according to Table 1.

Then, the evaluation judgment matrix P can be expressed as follows:

$$P = \begin{bmatrix} u_{11} \cdots u_{12} \cdots u_{1j} \cdots u_{1N} \\ u_{12} \cdots u_{22} \cdots u_{2j} \cdots u_{2N} \\ u_{i1} \cdots u_{i2} \cdots u_{ij} \cdots u_{iN} \\ u_{N1} \cdots u_{N2} \cdots u_{Nj} \cdots u_{NN} \end{bmatrix} = \begin{bmatrix} 1 \cdots 3 \cdots 2 \cdots 3 \\ \frac{1}{3} \cdots 1 \cdots \frac{1}{2} \cdots 1 \\ \frac{1}{3} \cdots 2 \cdots 1 \cdots 2 \\ \frac{1}{2} \cdots \frac{1}{3} \cdots 1 \cdots 1 \end{bmatrix}, \quad (2)$$

$$\lambda_{\max} = \frac{1}{n} \sum_{i-1}^{n} \frac{\sum_{i-1}^{n} \mu_{ij} \beta_j}{\beta_i},$$

where $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix.

Matrix, >0, = 1, =, = (1, 2, ..., 10), among i = (1, 2, ..., N); and j =(1, 2, ..., N). This can be judged that the eigenvector of matrix P is $\beta = \{\beta_1, \beta_2, \ldots, \beta_N\}^T$, next we collate and calculate $\beta = (0.45, 0.142, 0.267, 0.142)^T$, $\lambda_{\max} = 4.1198$.

Here, $q(u_i)$ is the ratio relationship between the eigenvalues of similar elements of the badger's claw toe structure and the rotary tillage knife structure in the fuzzy similarity system [17].

In this way, we can know that the similarity between them is $q(u_i) = (0.75, 0.6, 0.8, 0.5,)$; finally, the similarity between the badger's claw toe and the rotary tillage knife is

$$Q = 0.45 * 0.75 + 0.142 * 0.6 + 0.267 * 0.8 + 0.142 * 0.5 = 0.7073. \quad (3)$$

Through the analysis and calculation of the fuzzy similarity, it can be seen that the claw toe of the badger is more similar to the rotary tillage knife, so the claw toe of the badger can be used as the prototype for bionic optimization design of the rotary tillage knife [18].

3.3. Extraction and Inspection of Contour Curve. There are generally two ways to extract the characteristic curve of the badger's claws and toes. The first is to extract the samples of the badger's claws and toes, cut the badger's claws and toes, extract the slice samples of the claws and toes, and view the slices with an electron microscope or light microscope. Whether it meets the requirements, we then clean and dry the part and analyze and measure it with image analysis software to extract the curves of the upper and lower surfaces of the badger's claws and toes, so as to carry out bionic optimization design [19].

The second method is to collect the front and side images of the badger by a camera, three-dimensional scanner, or other means, use MATLAB software to ashing the collected images to obtain the pixel curve of the shape of the badger's claw and toe, then extract the original coordinate data from the curve, and get the fitting curve equation of the badger's claw and toe through MATLAB curve fitting. The 3D model construction and 2D drawing are carried out through UG. According to the actual conditions, the second scheme is selected [20]. The basic process is shown in Figure 2.

In MATLAB, the rgb2gray function is used to gray the badger's claw toe image. The built-in function of MATLAB is called to obtain the claw toe image contour, extract the fingertip original data coordinate points, import the x-axis coordinate and y-axis coordinate into two documents respectively, and fit the original coordinates through the MATLAB curve fitting tool. Due to the soft and smooth contour of the badger's claw toe and the convenience of analysis and calculation, it was decided to use a polynomial function equation to fit the obtained image data [21]. As shown in Figures 3and 4, the coordinates of the badger's toe tip are shown.

The fitting equation is obtained by fitting the data in MATLAB: $R^2 = 0.9556$,

$$y = -3.467e - 06 * x^4 + 0.001296 * x^3 - 0.1909 * x^2 + 13.59 * x - 192.5. \quad (4)$$

Table 1: The scale/calibration of a judgment matrix.

Scale	Calibration
1	Indicates that the two factors being compared have the same importance
3	Indicates that one of the two factors being compared is marginally more significant than the other
5	Indicates that one of the two factors being equated is considerably more significant than the other
7	Indicates that one of the two factors being equated is enormously significant relative to the other
9	Indicates that one of the two factors being equated is exceptionally significant relative to the other
2, 4, 6, 8	Indicates that the two factors being equated are between the above two adjacent judgment values

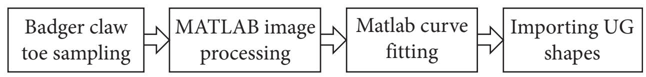


Figure 2: The curve fitting process.

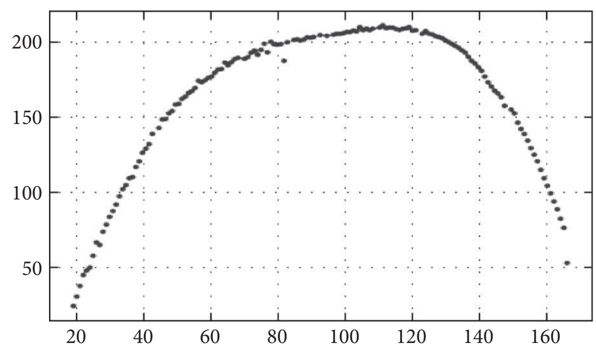


Figure 3: The coordinates of claw toe tip.

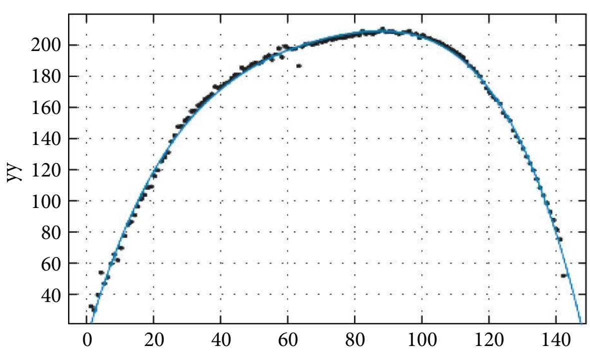


Figure 4: The fitting curve.

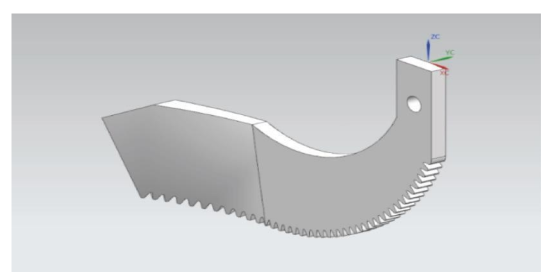


Figure 6: Full arrangement bionic rotary tiller model.

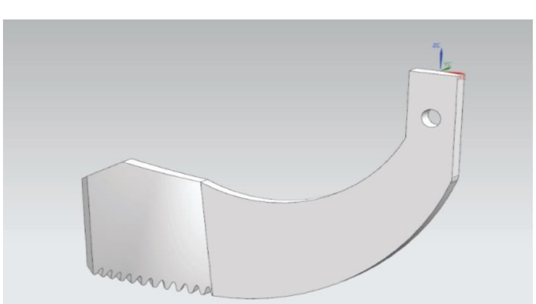


Figure 5: The bionic rotary tiller model with tangent blade arrangement.

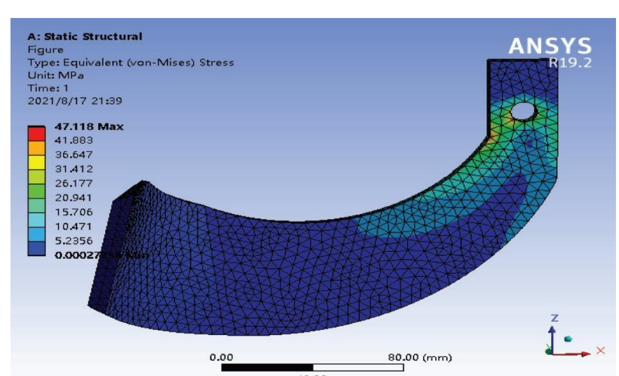


Figure 7: Equivalent stress diagram of the ordinary rotary tiller.

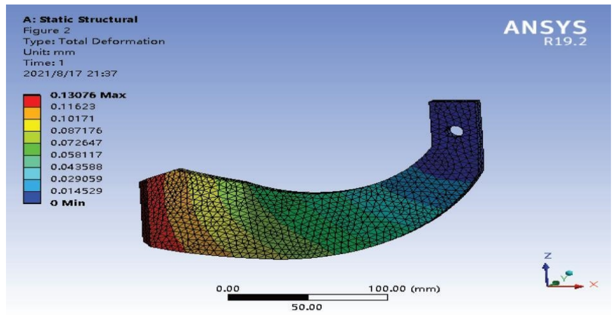
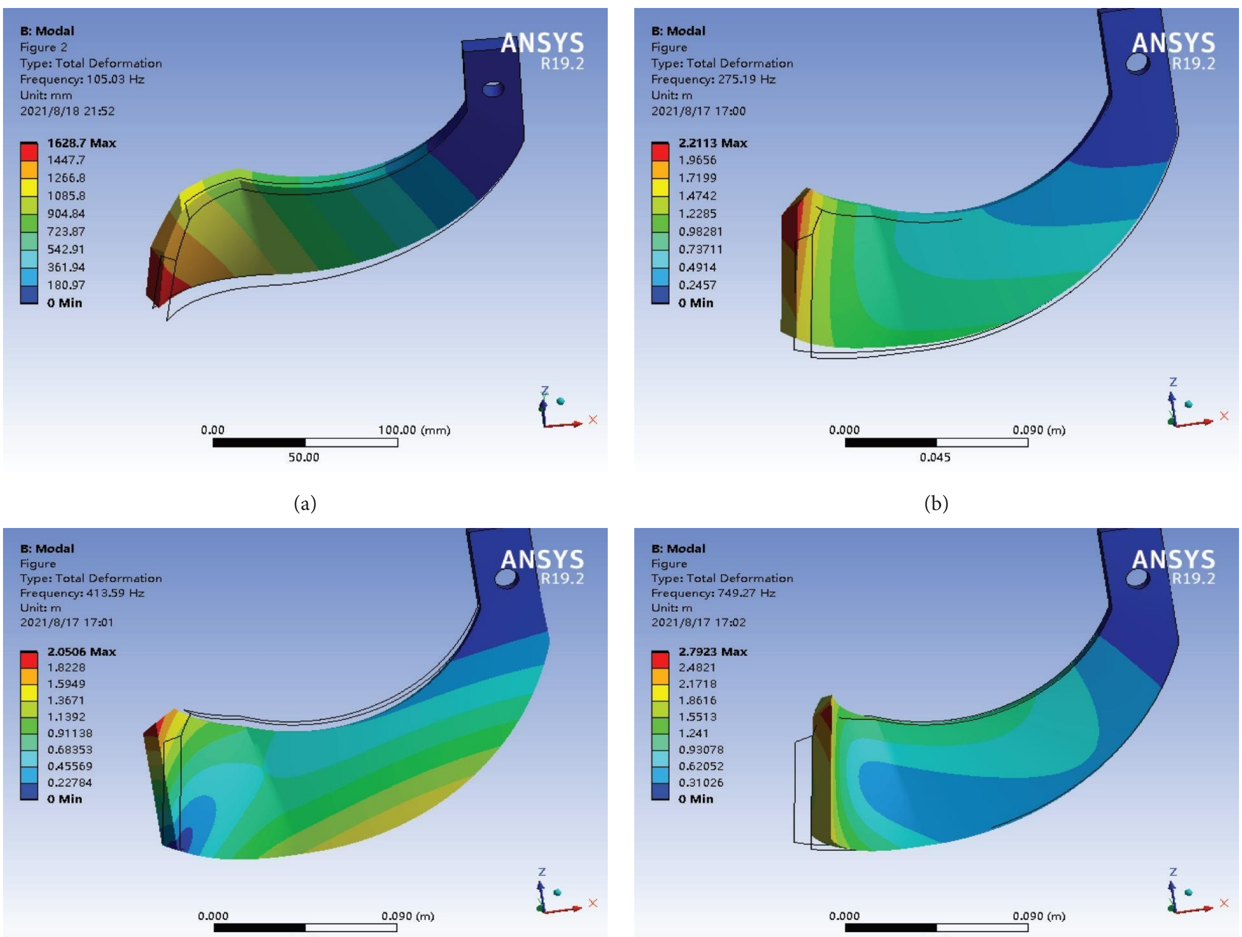
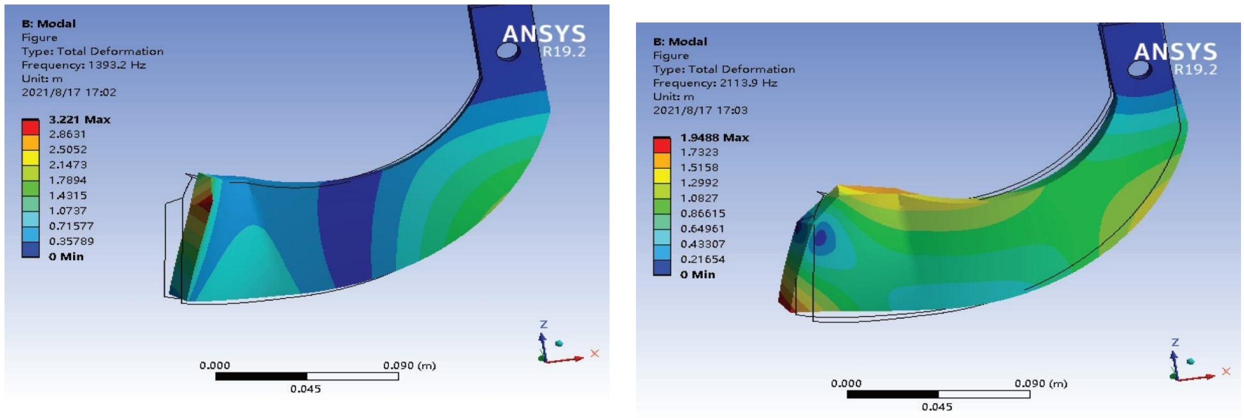


FIGURE 8: Deformation of the ordinary rotary tilla tillage knife.



(a) (b)

(c) (d)



(e) (f)

Figure 9: Sixth-order modal analysis diagram of the ordinary rotary tillage knife (a–f).

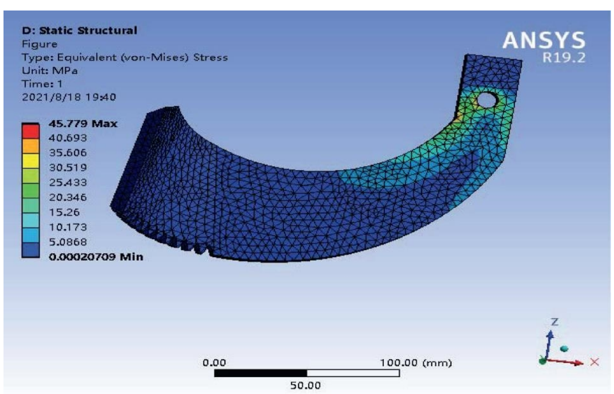


Figure 10: Equivalent stress of tangent blade arrangement.

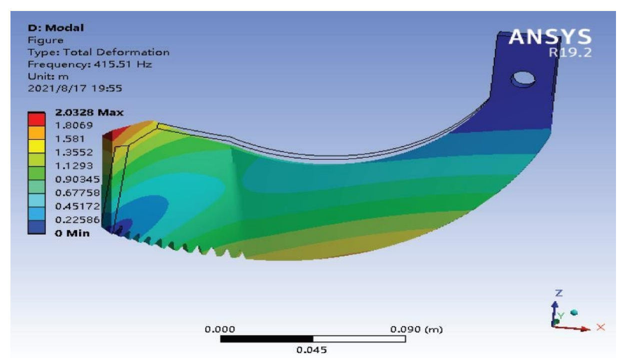


Figure 11: Deformation diagram of tangent blade arrangement.

4. Optimization Analysis of Bionic Rotary Tiller

4.1. Modeling of Bionic Rotary Tiller. Based on the three-dimensional discrete element model experiment established by Fang Huimin et al. [22, 23], the bionic rotary tiller model is constructed. We drew a sketch of the connection between the transition edge and the tangent edge. The regular curve in the UG only supports the parameter equation, so it is necessary to convert the fitting equation into the parameter equation available in the UG.

$$y = -3.467e - 06 * x^4 + 0.001296 * x^3 - 0.1909 * x^2 + 13.59 * x - 192.5. \quad (5)$$

The value range of X is 20 ~ 180. The default parameter of the UG is t, and t is the continuous number of 0 ~ 1 changes. Therefore, the parameter equation of X is

$$\begin{aligned} x &= 20 + 160t, \\ yt &= -3.467e - 6 * xt\hat{4} + 0.001296 * xt\hat{3} \\ &\quad - 0.1909 * xt\hat{2} + 13.95 * xt - 192.5. \end{aligned} \quad (6)$$

We wrote the above parameter equation into the UG expression tool, generate the curve through the regular equation, copy it to the sketch plane established by the previous knife surface, move it to the intersection of the tangent edge and the transition edge of the rotary tillage knife, adjust the length and width, the stretching length is 10 mm, evenly arrange the stretched entities on the tangent edge along the curve array, and then subtract the stretched entities and the entities obtained by the array from the rotary tillage knife as a whole. The bionic rotary tiller model with sawteeth arranged along the tangent edge can be obtained. On this basis, after the stretched solid model is arrayed along the side cutting edge, and then the stretched features and array features are subtracted, the bionic rotary tiller with sawtooth is fully arranged along the tangent edge and a side cutting edge can be obtained. The solid models of the two rotary tillers are shown in Figures 5 and 6.

4.2. Finite Element Analysis of the Prototype and the Bionic Rotary Tiller. We applied corresponding constraints and loads to the ordinary rotary blade, respectively, conducted static analysis on the ordinary rotary blade, selected the total deformation and stress distribution as the solution options, and obtained the stress distribution diagram and deformation diagram of the ordinary rotary blade, as shown in Figures 7 and 8. After the static analysis is completed, drag the modal analysis option into the working area in the Workbench working interface to align the static analysis options. The data such as material and grid division can be shared, and the modal analysis is carried out for the ordinary rotary tillage knife, and the modal analysis does not apply the load, but only constraints. After the analysis, the first to sixth order vibration mode diagrams of the ordinary rotary tillage knife are obtained, as shown in Figure 9, in which the fifth order vibration mode is edge warping, and the other vibration modes are in plane warping.

The stress diagram and deformation diagram of the bionic rotary tiller with tangent blade arrangement are obtained through static analysis, as shown in Figures 10 and 11. After the static analysis is completed, the modal analysis of the bionic rotary tiller with tangent blade arrangement can be carried out on this basis, and the vibration mode diagrams of order 1 ~ 6 are obtained, as shown in Figure 12.

The static analysis of the fully arranged bionic rotary blade is carried out, and the stress diagram and deformation diagram are obtained, as shown in Figures 13 and 14. On the basis of statics, the modal analysis of the fully arranged bionic rotary blade is carried out, and the vibration mode diagrams of order 1 ~ 6 are obtained, as shown in Figure 15.

4.3. Analysis of Bionic Optimization Results of the Rotary Tillage Knife. The practical significance of structural efficiency is studied by reference to materials and is closely related to strength, stiffness, and weight. According to the design criteria and the evaluation basis of structural efficiency, the specific strength and specific stiffness of the rotary tillage knife are calculated. The specific stiffness and strength of the bionic body and the prototype are obtained and analyzed. Specific strength and specific stiffness are also important indicators that reflect the stability of the structure. Through the comparison, we can get the performance of bionic and prototype in strength and stiffness. The greater the specific stiffness and strength value, the better the stiffness and strength performance of the structure.

$$\text{Structural efficiency} = \frac{(\text{Material ultimate strength/structural stress})\,x\,(\text{Material elastic modulus/structural deformation})}{\text{Structural weight}},$$

$$\text{Specific strength and structural efficiency} = \frac{(\text{Material ultimate strength/structural stress})}{\text{Structural weight}},$$

$$\text{Specific stiffness structural efficiency} = \frac{(\text{Material ultimate strength/structural deformation})}{\text{Structural weight}}. \tag{7}$$

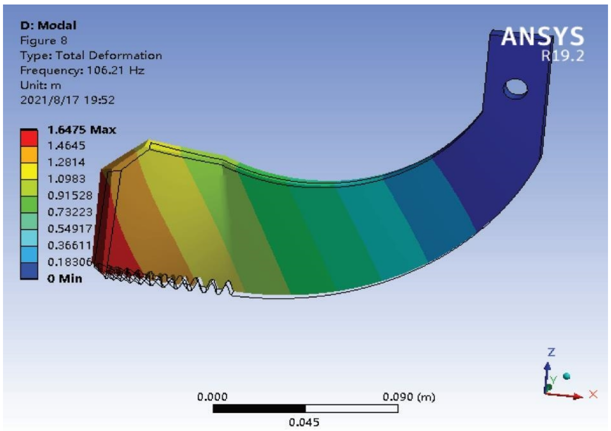
The data in Tables 2 and 3 are obtained through a calculation using the above formulas.

5. Discussion

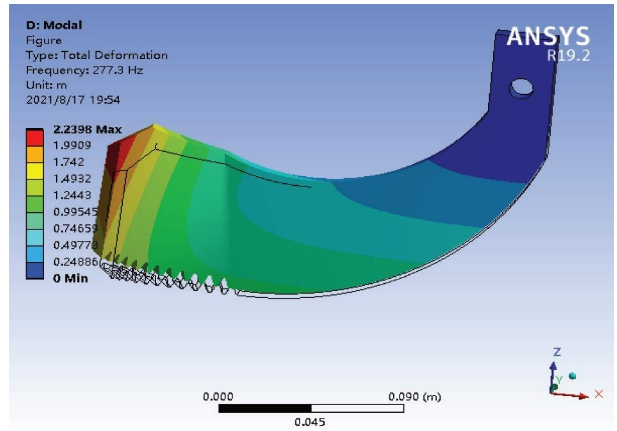
Through the research and analysis of the functional and structural characteristics of the badger's claw toe, taking the badger's claw toe as the bionic prototype, the IT245 rotary blade is optimized. The structural characteristics of the badger's claw toe are applied to the blade part of the rotary blade, and the optimized bionic rotary blade is obtained, which improves the sliding cutting effect of the blade, straw, and weeds. Through finite element static analysis and modal analysis, the experimental results show that the weight reduction, stress, and deformation of bionic rotary tillage knives are improved compared with ordinary rotary tillage knives. Through the calculation and analysis of mechanical properties, it is concluded that the specific stiffness, specific strength, and specific structural efficiency of the two bionic rotary tillage knives have also been improved.

(1) It is determined that the working load of the rotary tillage knife is 522N, and the tangent and side cutting edges of the rotary tillage knife are the stress plane. Through the finite element analysis, it is found that the maximum deformation of the ordinary rotary tillage knife is 0.13076 mm, which occurs at the tip of the rotary tillage knife. Towards the knife seat, the deformation gradually decreases, and it is zero near the knife seat. The maximum stress is 47.778 MPa, which is concentrated at the connection with the knife roller.

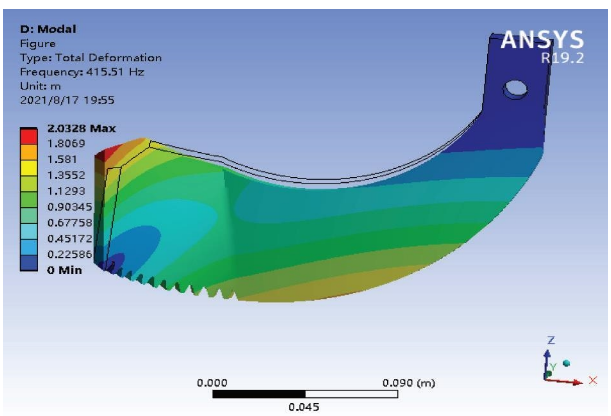
(2) The working conditions of the two bionic rotary tillage knives are the same as that of the ordinary rotary tillage knife. The analysis results show that the self-weight of the tangent blade arranged bionic rotary tillage knife of the tangent blade sawtooth arranged bionic rotary tillage knife is reduced by 0.0111 kg, 0.94%, and the self-weight of the fully arranged bionic rotary tillage knife is reduced by 3.31%. Furthermore, the strain and stress are reduced by 5.2% and 2.84%, respectively, when compared with an ordinary rotary tillage knife. The specific stiffness, specific strength, and specific structural efficiency are increased by 6.49%, 3.996%, and 11.364%, respectively. The stress of the bionic rotary tiller with full serration is to be observed approximately 7.38% lower than that of the ordinary rotary tiller, and the strain increases slightly, but the increase is small. Within the acceptable range,



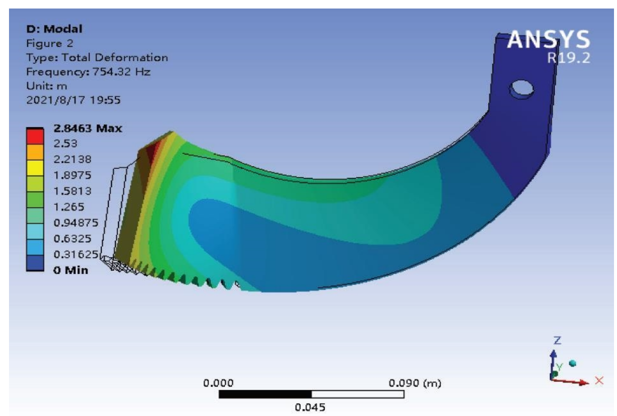
(a)



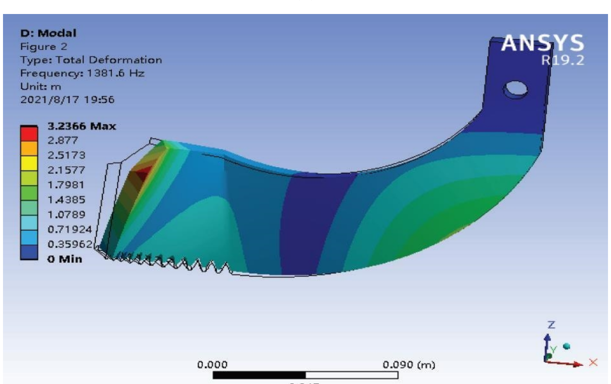
(b)



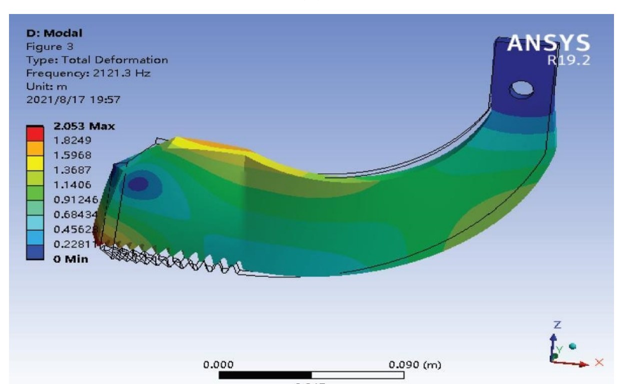
(c)



(d)



(e)



(f)

FIGURE 12: Sixth-order modal analysis diagram of the rotary tillage knife with tangent blade arrangement (a–f).

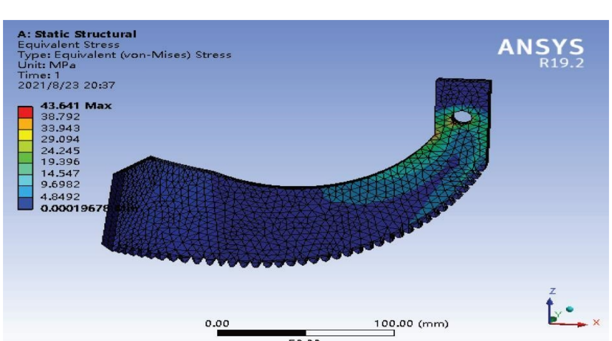


FIGURE 13: Full arrangement equivalent stress.

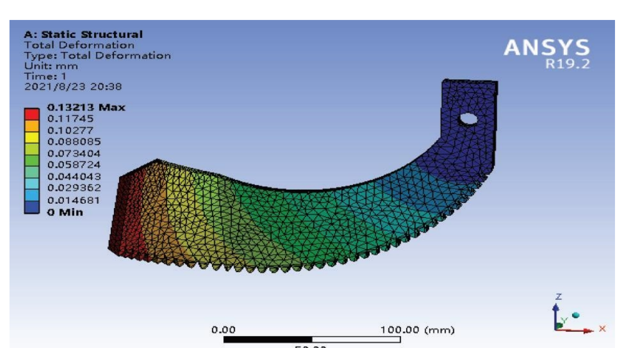


FIGURE 14: Deformation diagram of full arrangement type.

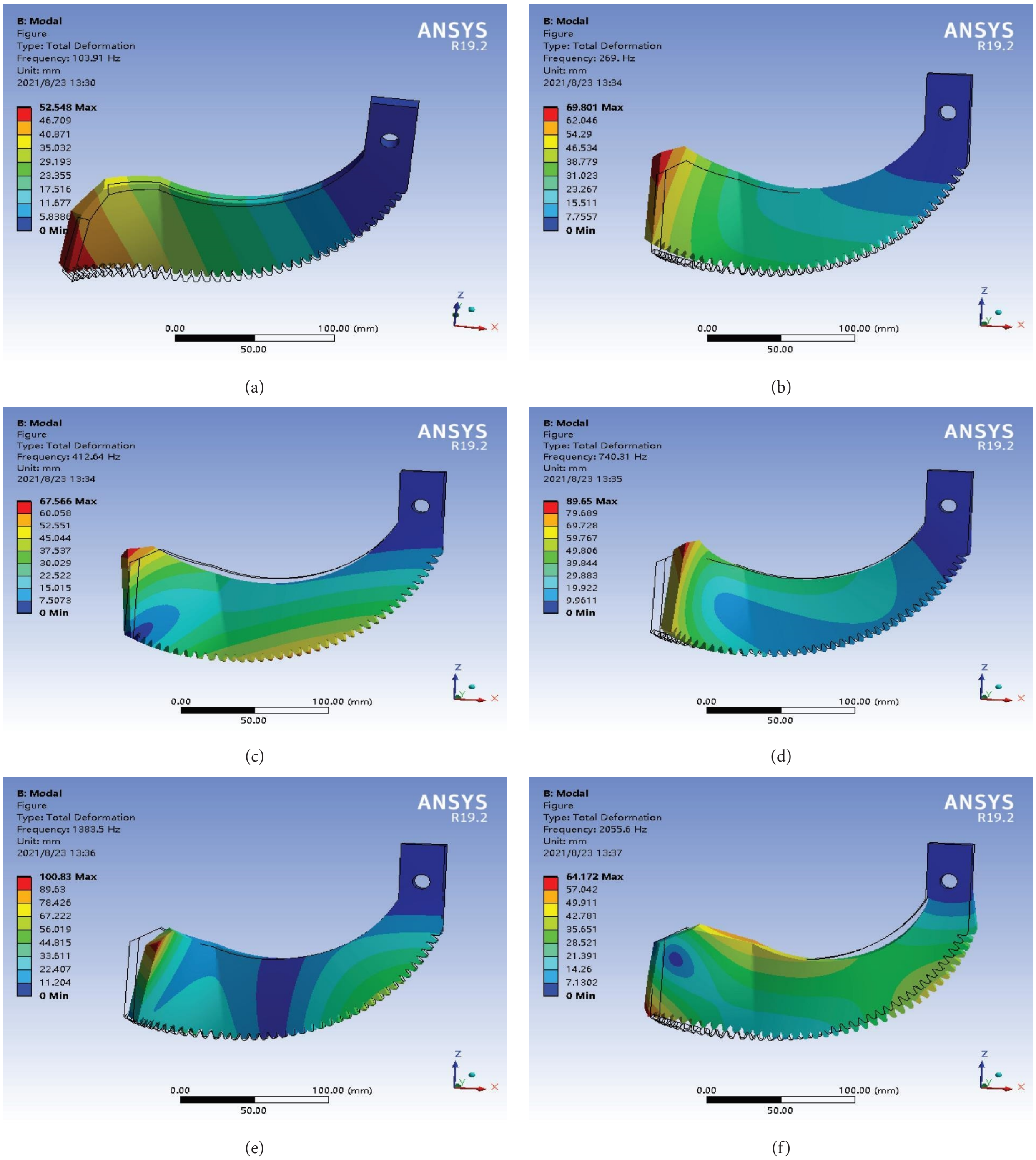


Figure 15: Sixth-order modal analysis diagram of fully arranged bionic rotary tillage knife (a–f).

the specific stiffness, specific strength, and specific structural efficiency are increased by 2.37%, 11.966%, and 14.64%, respectively. The weight of the bionic rotary blade is lower than that of an ordinary rotary blade. A comprehensive comparison shows that the weight, strain, stress, and mechanical properties of the bionic rotary blade are better than those of the ordinary rotary blade.

Table 2: The effectiveness data sheet.

	Rotary blade prototype	Tangent blade arrangement type	Full arrangement type
Structural efficiency	0.00444	0.0049	0.00509
Specific strength and structural efficiency	0.00351	0.00365	0.00393
Specific stiffness structural efficiency	1.264	1.346	1.294

Table 3: The data sheet of optimization results.

	Rotary blade prototype	Tangent blade arrangement type	Full arrangement type	Tangent blade arrangement increased (decreased) (%)	Full array increase (decrease) (%)
Specific strength	0.00351	0.00365	0.00393	3.996	11.966
Specific stiffness	1.264	1.346	1.294	6.49	2.37
Structural efficiency	0.00444	0.0049	0.00509	11.364	14.64
First-order mode (Hz)	105.03	106.21	104.16	1.12	−0.92
Second-order mode (Hz)	275.19	277.3	269.92	0.	−1.92
Third-order mode (Hz)	413.59	415.51	413.91	0.464%	0.08
Fourth-order mode (Hz)	749.27	754.32	741.89	0.674	−0.9
Fifth-order mode (Hz)	1393.2	1381.6	1387.7	−0.833	−0.395
Sixth-order mode (Hz)	2113.9	2121.3	2061.5	0.35	−2.49
Weight (kg)	1.2703	1.2584	1.2282	−0.94	−3.31
Maximum stress (MPa)	47.118	45.779	43.641	−2.84	−7.38
Maximum deformation (mm)	0.13076	0.12397	0.13213	−5.2	1.05

6. Conclusions and Future Work

In order to improve the structural performance of the rotary tillage knife, the badger claw toe was selected as the bionic prototype of the rotary tillage knife, and the bionic optimization design of the rotary tillage knife was carried out. The structural similarity between the badger's claw toe and rotary tiller is 0.7073 by fuzzy algorithm, and the shape goodness of fit between the final mole's claw toe and digging shovel is 0.9556 by MATLAB. Using 3D modeling software NX10.0, we established a three-dimensional model of the rotary tillage knife, used Workbench to carry out static analysis on the three rotary tillage knives, obtained their stress and deformation, obtained their vibration frequency through modal analysis, and summarized and compared the experimental data. The results show that compared with the ordinary rotary tillage knife, the proposed approach has superior results.

We will continue this work while proposing new algorithms for further improvement of the proposed model. In the near future, we intend to implement the particle swarm optimization (PSO) algorithm and other artificial intelligence techniques to solve the mentioned optimization problem. In fact, PSO has the capability to solve multiobjective optimization with a high convergence rate. We also intend to reduce the algorithm computational complexity when the optimization problem is considered a multiobjective.

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 there are no conflicts of interest.

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