Research Article

Design and Optimization of Working Parts of Vertical Spiral Ditching Machine Based on Milling Force and BP Neural Network Model

Guo Chen
ShanDong HuaYu University of Technology, Dezhou, Shandong 253034, China

Correspondence should be addressed to Guo Chen; chenguo114114@126.com

Received 14 March 2022; Revised 29 March 2022; Accepted 31 March 2022; Published 28 June 2022

Academic Editor: Liping Zhang

Copyright © 2022 Guo Chen. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The existing vertical spiral ditching machine mainly works in flat orchards, and the structural design of ditching components does not match the design of power transmission system, which leads to high ditching power consumption and poor ditching stability. According to the needs of deep application of organic fertilizer in orchards, a spiral cutter was designed to alleviate the common problems of high power consumption and poor stability of ditching machine and reduce the power consumption of ditch cutting. Therefore, the motion parameters and structural parameters of the spiral cutter are optimized. Using ANSYS preprocessor, the finite element model of cutting soil with spiral cutter is established, and the implicit functional relationship between milling force factor and instantaneous cutting thickness is established by using BPNN (BP neural network). On the basis of the established prediction model of milling force, orthogonal experiments were carried out to obtain the best combination of cutter head rotation speed, slotting depth, and advancing speed with minimum power consumption: 20.16 rad/s, 0.3 m, and 0.12 m/s. By investigating the influence of various working parameters on the power consumption of ditching machine, the analysis basis is provided for selecting reasonable working parameters of ditching machine.

1. Introduction

Ditch fertilization is an important part of orchard agricultural management. Ditching can help to loosen the soil and promote root growth. Fertilization can help fruit trees withstand stress and produce more fruit. Fertilization in orchard ditches is still primarily a manual operation, despite its importance in maintaining the quality of fruit trees and increasing production [1]. In China, most ditching machines are designed to work with medium and large tractors, and no ditching machine is designed to work with a microcomputer. This makes digging ditches that are not accessible by large tractors difficult. With China’s new orchard planting pattern, technology research and development has been prioritized. Currently, new orchards mostly use the method of close dwarf tree planting, while old orchards are transformed by sparse withered trees and close planting of big trees, allowing for mechanized and efficient orchard management [2].

The vertical spiral ditching machine’s working part is a set of spiral cutters that can mill, lift, and throw soil all at once. Small working parts, high working efficiency, flexibility, and hole length, among other features, are all advantages of the machine. For orchard groove operation, the vertical spiral groove is ideal [3, 4]. Under the conditions of no-tillage and stumps, Ye et al. studied the variation coefficient of sowing depth and sowing uniformity of each row of single disc and shovel ditching machines of various sizes [5]. Bao et al. investigated the impact of no-tillage furrow sowing on seedling emergence at three different operating speeds: single disk, hoe shovel, and backhoe shovel opener. After no-tillage flowering, the emergence rate of 4.75 km/h opener was the highest [6]. Wang et al. created an offset vertical spiral ditching machine that is unaffected by canopy branches and leaves and then tested it in a jujube vineyard [7]. To reduce the power consumption and vibration of the biaxial vertical spiral groove with counter rotation, Zi and Basti used the finite element method and smooth particle
hydrodynamics method [8]. The crawler minichain ditching machine, which is equipped with a remote control device and can walk freely on a slope of about 20°, was specially designed by Yichuan et al. It is a new type of miniature remote control vertical spiral ditching machine [9] that is suitable for robbery, particularly orchard operation. Due to a lack of domestic research, reference materials, theoretical research, and industry standards, the design of a vertical spiral ditching machine has the issue of incorrectly selecting operating and structural parameters. As a result, it is critical to thoroughly investigate the spiral cutter’s soil cutting mechanism, design and optimize the power and structural parameters, reduce the energy consumption of the ditching machine, and increase the mechanization level of fruit production.

Product quality and production efficiency are two of the most important considerations in modern manufacturing, and the best process conditions must be chosen during the process design stage or program design. As a result, whether it is to improve machining accuracy and efficiency or to implement virtual manufacturing, it is critical to establish an accurate and reliable cutting process model. One of the most important research topics [10, 11] is the development of a surface error model. This paper designed the main working parts of a vertical spiral ditching machine based on the requirements of deep application of organic fertilizer in orchards and on the design experience of predecessors. This paper focuses on the soil cutting process of a screw cutter combination and optimizes the dynamic and structural parameters of the screw cutter combination to reduce the ditching machine’s soil cutting power consumption. Based on the milling force model, two cutting force analysis indexes, the change of cutting force, are extracted from the curve, and the calculation method of the actual cutting depth is analyzed, starting with the analysis of the change of cutting area and progressing through the analysis of the overlapping degree of multiple teeth and the study of shape characteristics.

1.1. Innovation

(1) According to the working quality standard of ditching machine on the spot and the requirements of gardening technology on the actual working performance of ditching machine, the process of milling soil with spiral knife was numerically simulated and analyzed. ANSYS preprocessor is used to establish the finite element model of cutting soil with spiral cutter, apply loads and boundary conditions to cutter and soil, and export the key file of soil cutting

(2) Based on the prediction modeling of milling force, the optimal operating parameters of groove under the condition of minimum power consumption were obtained by orthogonal test. According to the influence of various motion parameters of the ditching machine on the power consumption of the ditching machine, some guiding suggestions are provided for the actual operation of the ditching machine

This paper is divided into five chapters, and the organizational structure is as follows:

The first section introduces the research background and significance before moving on to the paper’s main work. The second section focuses on the related technologies of design and optimization of the vertical spiral ditching machine’s working parts. The research’s specific methods and implementation are presented in the third section. The fourth section verifies the research model’s superiority and feasibility. The full text summary is the fifth section.

2. Related Work

2.1. Research Status of Ditching Machine. In recent years, scholars at home and abroad have done a lot of research on vertical spiral groove. Wu et al. created a “sine wave exponential curve-circular arc” combined ditching cutter that was installed on a disc-type vertical spiral ditching machine and tested in an orchard [12]. Yu et al. designed the key parameters of the arc opener of a wheat no-tillage planter, such as the slope and entry angle, and investigated the opener’s resistance at various working speeds [13]. Liu et al. expanded the application range of ditching machines by equipping these blocks with chains and blocks of various materials and sizes, such as cup teeth, rock teeth, and frozen soil teeth, based on different soil materials and hardness [14]. The spiral ditching machine was designed and developed to meet the agricultural needs of covering soil in wheat furrows. It has good soil throwing performance, high adaptability, and low power consumption. 65Mn steel is used to make the spiral blades [15]. Huang et al. conducted numerous heat treatment experiments on spiral blades at the same time to determine the best process route for spiral blade heat treatment [16]. Cheng et al. invented an automatic ditching machine that can excavate clay, sand, and gravel soil and is used for small-scale pipeline projects such as telecom fiber trench and cable trench [17]. Jiang et al. created a compact walking tractor-compatible cylindrical variable pitch rotary orchard drainage system. The device is simple in design, low in cost, cost-effective, and practical [18]. Cao et al. simulated the mechanical properties of the soil during cutting by developing a suitable soil composition model that incorporates different cell division shapes and boundary conditions of cutting soil to better simulate the interaction between soils and predict stress distribution and deformation of soil and cutting tools [19]. In cohesive soil, Xj et al. performed a finite element simulation on cutting with a linear cutting edge tool [20].

2.2. Research Status of Milling Force Prediction Model. With the continuous development of the automatic manufacturing system, the requirement for the monitoring function of cutting state is getting higher and higher. How to find the tool wear and replace the worn tool in time is the key to ensure the product quality and the normal operation of the automatic cutting process. Scholars at home and abroad have put forward many monitoring tools, among which cutting force monitoring is considered one of the methods with practical application potential, and the research of cutting force modeling and control method is the basis to solve this problem.
High-speed milling is a cutting-edge manufacturing technique that has gained popularity and development in the last ten years. High cutting speed, large feed, high machining accuracy, and good surface quality are all features of this machine. Milling force has a large influence on tool wear and damage in high-speed milling, so accurate cutting force prediction can be used to analyze the mechanism of high-speed milling and provide guidance.

Empirical formula modeling describes the relationship between milling force and cutting geometric parameters using a set of milling force coefficients. Cutting experiments on workpieces of various materials were carried out under various cutting conditions with cutters of various materials and geometric parameters, yielding a large number of milling force test data. Curve fitting can be used to calculate the uncertainty coefficient. The model with constant cutting force coefficient has greater prediction error, according to a comparison of cutting force coefficient, average cutting thickness constant, and exponential function. To fit the relationship between cutting force coefficient and cutting parameters, Hu et al. used the quadratic response surface method (cutting speed, feed per tooth, axial cutting depth, and radial cutting depth). The sum coefficient is calculated using the least square method [21], and the cutting force coefficient is a quadratic polynomial. Qu et al. show that the cutting force coefficient has little effect on the prediction effect, regardless of whether the edge effect is taken into account or not [22]. Tanaka et al. used artificial intelligence technology’s direct simulation method to establish the source equation and predict the cutting force [23]. This cutting process simulation system includes a technical database and a database, as well as experimental and analysis simulation capabilities. Based on the mechanism that the energy does not change during cutting and rigorous mathematical means, Kiswanto et al. systematically investigated the mechanical properties of the cutting edge of a ball-end end mill [24]. To apply the neural network model, Ray et al. proposed the finite element numerical simulation method and neural network modeling method [25], which both require a large number of samples for experiments. All finite element models necessitate the use of high-level professional software, which is inconvenient to use.

3. Methodology

3.1. Design of Working Parts of Vertical Spiral Ditching Machine

3.1.1. Spiral Blade Design. The main working principle of ditching machine is that the power is output by diesel engine and transmitted to the gearbox input shaft of ditching machine through belt drive. After being decelerated by the gearbox, part of the power is output to the electric tool and transmitted to the tractor transmission device through belt transmission, so that the whole device can move forward at low speed and crawl, and the reducer can provide stable traction.

The ditching machine spindle is driven to rotate by chain drive, which drives the chain cutter to rotate for ditching operation. During operation, the ditching knife on the hard side of the chain moves counterclockwise along the chain support to cut the soil line and form a ditch. When the ditching machine turns or pulls the ground, drive the hydraulic valve to lift the main beam to the highest position, and switch the gear box of the ditching machine to make the tractor return to the original speed, so as to run at low speed [11].

The spiral blade mainly plays the role of assembling the ditch blade, transmitting ditch torque, and transporting soil with the ditch blade. The soil particles cut in ditching operation are thrown into the ditch wall under the action of the centrifugal force of the spiral blade, which rubs against the ditch wall, making the rotation angular velocity lower than the rotation angular velocity, and the spiral blade slides upward along the ditch wall, which makes it possible to transport the soil.

Because the ditches in orchard operation are trapezoidal, single-line variable pitch spiral blades are not easy to block soil, so this paper uses single-line variable pitch conical spiral blades [15, 16]. The helix of the blade is a conical helix with equal slope and variable pitch, which is a spatial curve formed on the right conical surface. Helical angle is an important parameter, which is the angle between helical tangent and screw axis of medium diameter cylinder [15–17]. The three-dimensional model of the spiral blade is shown in Figure 1.

According to the main parameters of ditching machine, the upper diameter of spiral blade is \( D = 400 \text{ mm} \), the lower diameter is \( d = 200 \text{ mm} \), the length is \( H = 500 \text{ mm} \), and the thickness is \( \delta = 8 \text{ mm} \). The parameter equation is as follows:

\[
\begin{align*}
\rho &= ae^{mt} \\
x &= ne^{mt} \cos t \\
y &= ne^{mt} \sin t \\
z &= be^{mt}
\end{align*}
\]

Type \( n = a \sin \gamma \); \( b = a \cos \gamma \); \( m = \sin \gamma \cos \alpha \); \( a \) is the coefficient; \( \gamma \) is the cone top half angle; \( t \) is the independent variable; \( \alpha \) is the helix angle.

3.1.2. Screw Cutter Design. The structure and arrangement of ditching cutters have a significant impact on ditching machine performance. Chisels and machetes are examples of slotting tools that are classified primarily by their structural forms. A curved knife combines the advantages of both a chisel and a right angle knife. It has good structural properties, as well as good soil feeding and digging properties, and is difficult to cut. It can be used with an orchard disk trencher. Increase the adaptability of machine components. The grooving cutter is a commercial grooving machete with good soil throwing performance and can effectively transport soil. The cutter is made of 65Mn, which has a high wear resistance.

The stepped ditching cutter head is designed to uniformly install 6 ditching cutters on each layer of cutter head, and the ditching cutters of adjacent cutter heads are installed...
in different positions to ensure the stability of slotting and the continuity of soil excavation. The ditching knife has eighteen 30° stepped groove heads that are installed and bolted to the ditching cutter head’s cutter seat welded on the edge. The turning radius of the stepped slotting cutter head is determined to be 35 cm, 38.5 cm, and 42 cm after the slotting cutter is installed. Because the ditcher’s working parts are the bottom and side parts of the blade in the process of cutting soil, this study simplifies it. As shown in Figure 2, use the ditcher model.

The soil cutting process of ditching knife is complicated, and the stress and deformation of the knife change rapidly. Elastic deformation, plastic deformation, and sometimes fracture will occur. Because of these problems, it is necessary to simplify the analysis model in the finite element numerical motion analysis and modeling [15].

(1) It is assumed that the forward speed of ditching machine and the chain speed remain unchanged during the working process, and the magnitude and direction of the absolute speed of trenching remain unchanged.

(2) The speed combined with the forward speed of ditching machine and chain speed is the cutting speed of ditching cutter.

(3) Ignore the vibration of the knife when cutting soil, assuming that the ditching knife always moves on a certain plane.

The impeller of the traditional rotary tiller is mainly composed of several rotary tillers, which are installed on the shaft of the rotary tiller with a certain width and are suitable for rotary tillage of wide soil. Orchard ditching, ditching machine with double cutter disc ditching machine is different from traditional rotary tiller cutter roller, which is mainly equivalent to disc ditching operation in small format. However, the grooved blade of grooved cutterhead still has the kinematic characteristics of rotary tiller.

Taking the ditching blade of the cup-shaped machete as an example, the rotation center of the cutterhead wheel in the ditching process is set as the coordinate origin $O$, and the advancing direction of ditching machine is consistent with the horizontal direction of $v_m$. The movement direction of the horizontal axis is the $x$-axis direction, and the $y$-axis is vertically upward; then, the movement equation of the cutter wheel blade endpoint is expressed as

$$\begin{align*}
x &= R \cos \omega t + v_m t \\
y &= R \sin \omega t
\end{align*}$$

In the above formula, $R$ is the radius of rotation end point of cutter, mm; $\omega$ is the rotation angular velocity of cutter wheel, rad/s; $v_m$ is the advance speed of ditching machine, mm/s; $t$ is the exercise time, s.

Derive equation (2) with respect to $t$, and get the speed formula of the tip of the blade in the direction of $x, y$ axis:

$$\begin{align*}
v_x &= \frac{dx}{dt} = \omega R \sin \omega t - v_m t \\
v_y &= \frac{dy}{dt} = \omega R \cos \omega t
\end{align*}$$

The absolute speed of the end point of the blade is the blade cutting speed $v_c$:

$$v_c = \sqrt{v_x^2 + v_y^2} = \sqrt{v_m^2 - 2v_m R \sin \omega t + R^2 \omega^2}$$

3.2. Modal Analysis of Working Parts of Vertical Spiral
Ditching Machine. Finite element method is an efficient and common calculation method. Essentially, it discretizes a continuum into a group of elements with relatively simple geometric shapes. We solve this problem by connecting these discrete elements into nodes. The basic principle of the finite element method is to discretize the continuous solution domain into the combination of elements and to express the unknown long function found in the solution domain with the approximate function assumed for each element. By extending the derivative of the unknown field function to the numerical interpolation function of each node of the element, the approximate solution of the whole model is obtained. Obviously, the more discrete units, the higher the accuracy of interpolation function and the higher the accuracy of numerical solution.

The basic steps of complete finite element analysis should include the following:

1. In the modeling stage, the simplified finite element model is used to provide input data for numerical finite element calculation according to the actual shape and working condition of the structure. The main task of finite element modeling is to discretize the structure (mesh), which also includes defining element attributes, checking element quality, and numbering order and boundary conditions that must be specified in the model.

2. In the calculation stage, the task of the calculation stage is to complete the numerical calculation related to the finite element method. Because of the large amount of calculation, this part is controlled by finite element analysis software and completed on the computer.

3. In the postprocessing step, necessary processing is carried out on the calculated output results, useful results such as strain and stress are output, and the quality is analyzed by displaying or printing in a specific way through the graphical interface. The rationality of structure performance or design, improving and optimizing its structure to achieve the best effect, which is the purpose of performing structural finite element analysis.

Modal analysis is very important to understand and optimize the inherent dynamic characteristics of structures, and it is helpful to design lighter, stronger, and safer structures, thus reducing energy consumption and improving performance. It is hoped that the first five modes of the helical blade of the working part will be tested, the degree of freedom will be limited to 7, the working part will be suspended by flexible ropes, and accelerometers will be installed at equal intervals along the outer helical surface. Select a single random hammer excitation and run the modal analysis process, as shown in Figure 3.

Operating modal analysis approximates the excitation force signal to the filtered steady-state zero-mean Gaussian white noise, which means that there is no need to measure the excitation force, which greatly simplifies the test process and shortens the test time. From the measured response, the modal model of the combined estimation structural system...
is extracted from the estimation model of the combined system [4].

Use the free mesh method to mesh the working part, enable the intelligent size control, and select the six-step segmentation accuracy. The quality of the mesh has little influence on the results of finite element modal analysis, so the fine-grained mesh model on the local mesh is shown in Figure 4.

The boundary conditions of finite element modal analysis can be divided into free mode and constrained mode. In the running mode test, the method of suspending the working part can be used to approach the free boundary. As a result of running modal test, free boundary is used for finite element modal analysis. That is to say, the finite element model of the working part has no freedom limit.

Table 1 gives the description of natural frequencies and vibration modes of the working part of spiral groove in completely free state. From the table, it is not difficult to find that the frequency distribution of each order is reasonable. The natural frequencies of the first three orders of the working part are 0, and the natural frequencies of the fourth to sixth orders are very small, that is, they are almost the same as the first six orders obtained by free mode analysis. This is because the mode is a rigid-body mode, and the shape of the mode includes three translation and three rotation parts of the whole rigid body.

Through the above analysis, we can get the vibration form of the working part in the free state. Because the mass of the main shaft is heavier than that of the spiral blade, the bending vibration of the main shaft is dominant at low rotational speed. The axial vibration of spiral blade is the main mode of higher order, which compensates the torsional vibration of spindle.

### 3.3. Optimization of Cutting Parameters

#### 3.3.1. Milling Force Prediction Modeling

To realize the above milling force modeling concept, the tool must first be given a detailed and accurate geometric description (description of inclination angle, helix angle, helix delay angle, and shaft angle), and then, each microsegment cutting process must be solved. Finally, we must determine the number of microsegments involved in cutting at the current rotation angle for that coordinate transformation matrix. The slope cutting force coefficient model is the most significant difference between the prediction modeling of milling force in this paper and existing modeling methods.

Typical end mills generally have more than two cutting edges evenly distributed around their circumference, and the helix angle of cutting edges is generally in the range of $200^\circ$~$500^\circ$. For the convenience of analysis, it is assumed that the length of the tool involved in cutting is $z$ (along the axial direction of the tool), and if the cutting edge of the tool is equally divided into $N_z$ equal parts along the axial direction, that is, $dz = z/N_z$. Then, the axial distance of the cutting microsection $\{i,j\}$ from the bottom of the tool can be expressed as

$$z_{ij} = j \cdot dz = j \frac{z}{N_z}, \quad i = 1, 2, \ldots, N_i; \quad j = 1, 2, \ldots, N_z$$

In the formula, $i,j$ stands for meaning consistent with the meaning of cutting microsegment $\{i,j\}$.

According to the actual milling process, it can be seen that the three-dimensional forces on the cutting microsegment $\{i,j\}$ pair are tangential force $F_{i,j,T}$ along the spiral cutting edge, radial force $F_{i,j,R}$ perpendicular to the cutting edge on the rake face and circumferential force $F_{i,j,a}$ perpendicular to the rake face.

Based on the model of cutting force coefficient on rake face, the cutting force coefficient in three directions along rake face is $K_r, K_t, K_a$, so the milling force can be expressed as the product of cutting force coefficient and instantaneous cutting area. Therefore,

$$\begin{align*}
F_{i,j,T} &= K_r \cdot dA' \\
F_{i,j,R} &= K_t \cdot dA' \\
F_{i,j,a} &= K_a \cdot dA'
\end{align*}$$

| Order | Natural frequency/Hz | Describe vibration mode |
|-------|----------------------|-------------------------|
| 1     | 0                    | Rigid body translation  |
| 2     | 0                    | Rigid body translation  |
| 3     | 0                    | Rigid body translation  |
| 4     | 213.68               | Spindle bending vibration|
| 5     | $2.5 \times 10^{-3}$ | Rigid body rotation     |
| 6     | 566.1                | Spindle bending vibration|
| 7     | 812.9                | Axial vibration of spindle and torsional vibration of spindle |
| 8     | 1028.6               | Axial vibration of spiral blade |

| Level | $V_{\text{speed}}$(rad/s) | Factor $D_{\text{depth}}$(m) | $V_{\text{advance}}$(m/s) |
|-------|---------------------------|-----------------------------|--------------------------|
| 1     | 16.33                     | 0.30                        | 0.12                     |
| 2     | 18.01                     | 0.32                        | 0.29                     |
| 3     | 20.16                     | 0.35                        | 0.46                     |
When the tool rotation position is at the angle of \( \phi \), the instantaneous cutting resultant force is the vector sum of the cutting forces of all the cutting edges involved in cutting. Then, when the tool rotation angle is \( \phi \), the instantaneous cutting force of the whole tool in the \( X \), \( Y \), \( Z \) direction is

\[
F_X(\phi) = \sum_{i,j} F_{i,j,X}, \\
F_Y(\phi) = \sum_{i,j} F_{i,j,Y}, \\
F_Z(\phi) = \sum_{i,j} F_{i,j,Z}.
\]  

(7)

3.3.2. Optimization of Soil Cutting Parameters of Ditcher. When optimizing the soil cutting speed of the ditcher, the soil cutting thickness of the ditcher should also be considered. When the soil cutting speed of the ditcher decreases, the soil cutting thickness of the ditcher increases; otherwise, the soil cutting thickness decreases. Calculated by the following formula:

\[
V_a = \sqrt{V_L^2 + V_0^2 + 2V_L V_0 \cos \alpha}
\]  

(8)

In the above formula, \( V_a \) is the absolute cutting speed of ditching knife, m/s; \( V_L \) is the linear speed of ditcher chain, m/s; \( V_0 \) is the advance speed of ditching machine, m/s; and \( \alpha \) is the angle between the ditching chain and the horizontal plane is 25° when the ditching depth is 40 cm.

\[
\tan \beta = \frac{V_L \sin \alpha}{V_L \cos \alpha + V_0}
\]  

(9)

In the above formula, \( \beta \) is the angle between absolute cutting speed of ditcher and horizontal plane.

\[
\delta = L_c \sin (\alpha - \beta)
\]  

(10)

In the above formula, \( \delta \) is the thickness of soil cut by trenching knife, mm; \( L_c \) is the pitch between two ditching knives, mm.

When the chain speed is 1.6 m/s, the cutting thickness of the big knife and the small knife is the same, and the variation is 0.2 mm. When this cutting speed is brought into the ditching knife cutting model, the cutting power of a single blade at this speed is 0.162KW, which is 32% lower than that at 2.5 m/s.

3.3.3. Optimization of Ditching Machine Power. In order to understand the variation law of power consumption of ditching cutter head under different working parameters, we studied the working parameters that affect the power consumption of ditching and found out the best combination factor when the power consumption is the lowest. The rotating speed, advancing speed, and ditching depth of ditching cutter head were selected as the investigation factors, and the power consumption was used as the evaluation index. The virtual orthogonal test was carried out on the three factors by orthogonal test method.
Figure 6: Effect curve of influencing factors on power consumption.
In this experiment, three working parameters, i.e., cutterhead speed $V_{\text{speed}}$, ditching depth $D_{\text{depth}}$, and forward speed $V_{\text{advance}}$ of the ditching machine, are selected as experimental factors. According to the actual working conditions of the vertical spiral ditching machine, the test factor levels are shown in Table 2.

### 4. Experiment and Results

#### 4.1. Verification of Modal Analysis Results

The modal natural frequencies with rigid-body modes and repetitive roots are deleted from the results of free modal analysis of finite element, and the comparison results of natural frequencies of various modes obtained from modal analysis experiments are shown in Figure 5.

It can be seen from Figure 5 that the relative errors of modal frequencies 1 and 4 are relatively large, and the frequency errors of other orders are all within 3%. The correctness of the finite element theoretical model and analysis method established in ANSYS is verified by modal analysis test, which provides a strong theoretical basis for optimizing the structural parameters of working parts and can greatly save manpower and material resources. Reducing resources and capital investment is an important guide for spiral ditching machine design.

#### 4.2. Optimization Result Analysis of Working Parameters of Ditching Machine

Modify the $K$ file according to the motion parameters in Table 2 and submit it to the ANSYS solver for solving. After saving the analog data, use Ultra Edit to open the data and enter the analog power consumption results in the table. In order to explore the trend of trenching power consumption changing with the parameters of three factors, according to the test data of three factors and three steps, taking the level of each factor as the horizontal axis, taking the average value as the vertical axis, the influence curves of three influencing factors on trench power consumption are drawn, as shown in Figure 6.

### Table 3: Variance analysis.

| Index          | Source   | Degree of freedom | Sum of squares | Mean square | $F$   | Significance |
|----------------|----------|-------------------|----------------|-------------|-------|--------------|
| Power consumption | $V_{\text{speed}}$ | 3                 | 0.441          | 0.217       | 50.241| 0.018        |
|                | $D_{\text{depth}}$ | 3                 | 0.153          | 0.073       | 15.667| 0.055        |
|                | $V_{\text{advance}}$ | 3                 | 0.067          | 0.038       | 7.724 | 0.113        |
|                | Error    | 3                 | 0.003          |             |       |              |
|                | Total    | 8                 | 54.17          |             |       |              |
| After correction sum | 7       | 0.66              |                |             |       |              |

**Figure 7:** Comparison between the predicted value of milling force and the experimental value of cutting conditions (Experiment 2).
Figure 8: Comparison between the predicted value of milling force and the experimental value of cutting conditions (Experiment 3).

Figure 9: Comparison between the predicted value of milling force and the experimental value of cutting conditions (Experiment 4).
From level 1 to level 3, the power consumption of ditching tends to decrease with the increase of cutter head rotation speed, because when the cutter head rotation speed is low, the kinetic energy obtained by soil particles is small, and the soil cannot be cut, which leads to failure. The ditching knife cuts the soil repeatedly. With the increase of cutter head speed, the soil gains more kinetic energy, and the soil is successfully cut, and the repeated cutting in the soil is reduced, which shows that the power consumption is reduced.

In the process of advancing speed from level 1 to level 3, the power consumption of trenching increases with the increase of advancing speed, but with the further increase of advancing speed, the increase rate of power consumption slows down negligibly.

In order to further determine the significance of the influence of various influencing factors on the power consumption of ditching machine, SPSS software was used to analyze the variance of orthogonal test results. Table 3 shows.

According to the analysis of variance of orthogonal test, it can be seen that the rotating speed has a great influence on the power consumption of the groove, while the advancing speed has little influence on the power consumption of the groove. According to the significant results of variance analysis, the order of influence of various factors on working power consumption is consistent with the results of range analysis, that is, cutterhead speed > slitting depth > advancing speed. Optimal working parameter combination under the condition of minimum power consumption; \( V_{\text{speed}} = 20.16 \, \text{rad/s}, D_{\text{depth}} = 0.3 \, \text{m}, V_{\text{adv}} = 0.12 \, \text{m/s} \).

Therefore, in the actual working process of ditching machine, under the condition of meeting the requirements of orchard ditching agriculture, the ditching depth should be reduced as much as possible, and the rotating speed of cutter head should be appropriately increased to achieve it. The purpose is to reduce the power consumption of ditching machine. The advancing speed of the ditching machine has little influence on the power consumption, so in the actual working process, the working speed and efficiency of the ditching machine can be appropriately increased.

4.3. Experimental Verification of Milling Force Prediction Model. Different workpiece materials have different functional relationships between cutting force coefficient and cutting thickness. According to the given method of determining the cutting force coefficient of inclined plane, when milling aluminum parts with flat end mill, the milling force corresponding to one rotation of the cutter is extracted from the three-direction milling force measured in experiment 1. The established milling force prediction model can calculate the three-direction cutting force coefficient \( K_r, K_p, K_n \) corresponding to different cutting thicknesses, and the implicit functional relationship between cutting force coefficient and cutting force is established by using BP neural network.

For different experimental cutting conditions corresponding to different cutting thicknesses, each cutting force coefficient \( K_r, K_p, K_n \) can be obtained through the implicit functional relationship between cutting force coefficient and cutting thickness established by BPNN. Then, the milling force is predicted by the set milling force prediction model. The control results of cutting conditions according to Experiment 2, Experiment 3, and Experiment 4 are shown in Figures 7, 8, and 9.

It can be seen from the comparison results of these three groups of predictions and experiments that the predicted results are in good agreement with the experimental results, and the prediction accuracy is better under the same cutting conditions, which meets the actual application requirements.

5. Conclusions

Based on the milling force model, this paper analyzes and optimizes the designed vertical spiral ditching machine working parts with the help of 3D drawing software, finite element analysis software, Matlab optimization toolbox, and drawing function. The research and conclusions are as follows:

1. The free modal analysis of the working part of the vertical screw ditching machine is carried out by using ANSYS software, and compared with the test results of the running modal analysis, which verifies the correctness of the finite element analysis method.

2. Using orthogonal test method, the virtual orthogonal test of three factors and three levels is carried out for three working parameters that affect the power consumption of trenching. The optimal combination of operating parameters under the condition of minimum power consumption: the rotation speed is 20.16 rad/s, the trenching depth is 0.3 m, and the forward speed is 0.12 m/s.

3. In this paper, the three-dimensional cutting force coefficient can be obtained by the milling force prediction model, and the corresponding instantaneous cutting thickness can be recorded. Because the corresponding function can be obtained from the function after changing the cutting conditions, the milling force prediction is realized, and the accuracy of the milling force prediction model is verified by experiments.

Data Availability

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

Conflicts of Interest

The author does not have any possible conflicts of interest.

References

[1] J. Zhang, Z. Niu, T. Li et al., “Design and optimization of planting process parameters for 2ZYX-2 type green onion ditching and transplanting machine,” Phyton, vol. 89, no. 1, pp. 147–166, 2020.
[2] P. Lucretia, M. Eugen, V. Valentini et al., “Planting orchards by different technologies,” 5th International Conference of Thermal Equipment, Renewable Energy and Rural Development, p. 345, 2016.

[3] E. Jakobsson, “Ditching from a water system perspective. Draining the Swedish water landscape 1200–1900,” Water History, vol. 5, no. 3, pp. 349–367, 2013.

[4] Y. L. Chen, W. Qiu, W. M. Ding, Y. N. Li, and Y. T. Liu, “Improvement and test on ditcher chain transmission system of the machine for rice-wheat cyclic planting,” Applied Mechanics and Materials, vol. 644-650, pp. 853–857, 2014.

[5] Q. Ye, F. Xie, S. Sun et al., “Development of vineyard ditcher with reversal twin rotary tillage wheels,” Transactions of the Chinese Society of Agricultural Engineering, vol. 29, no. 3, pp. 9–15, 2013.

[6] W. Bao Panfeng, G. C. Mingliang, G. Chunyun, L. Haifeng, H. Yiming, and X. Wei, “Design of furrowing and ridging device for rape sowing with plough and rotation,” Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), vol. 33, no. 20, pp. 23–31, 2017.

[7] X. Y. Wang, L. W. Zhou, Q. R. Ren, J. H. Chen, and X. Q. Tang, “An integrated technology for 3D laser marking,” Advanced Materials Research, vol. 472-475, pp. 2489–2493, 2012.

[8] A. Zi, L. X. Basti, Contribution, and L. Xuanfeng, “Development of 1K-40 type offset orchard ditching machine,” Xinjiang Agricultural Mechanization, vol. 4, p. 2, 2009.

[9] H. Yichuan, T. Zhihui, M. Xiangjin, and Q. Tianrong, “Design and test of 2FK-40 orchard furrow fertilizing machine,” Research on Agricultural Mechanization, vol. 12, pp. 201–204, 2015.

[10] C. Xia, S. Wang, S. Sun, C. Ma, X. Lin, and X. Huang, “An identification method for crucial geometric errors of gear form grinding machine tools based on tooth surface posture error model,” Mechanism and Machine Theory, vol. 138, pp. 76–94, 2019.

[11] C. Yulun, D. Weimin, Y. Hongtu, D. Qishuo, and W. Xiaochan, “Design and experiment of combine harvester with function of stalk-discharging to ditch,” Nongye Xixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery, vol. 43, pp. 73–78, 2012.

[12] M. Wu, C. Guan, H. Luo, and C. Tang, “Design and experiments of 2BYD-6 shallow tilling and fertilizing seeder for rapes,” Transactions of the Chinese Society of Agricultural Engineering, vol. 26, no. 11, pp. 136–140, 2010.

[13] Y. Yu, S. Zhang, H. Li, X. Wang, and Y. Tang, “Modal and harmonic response analysis of key components of ditch device based on ANSYS,” Procedia Engineering, vol. 174, pp. 956–964, 2017.

[14] Y. Q. Liu, M. Q. Zhao, F. Liu et al., “Vibration test and analysis of no-till planter on the maize stubble surface,” Advanced Materials Research, vol. 1061-1062, pp. 788–793, 2014.

[15] A. Kapoor, “Conflict denied ops,” Living Digital, vol. 13, no. 4, p. 80, 2008.

[16] H. Dongyan, Z. Longtu, J. Honglei, and Y. Tingting, “Automatic control system of seeding depth based on piezoelectric film for no-till planter,” Nongye Xixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery, vol. 46, no. 4, pp. 1–8, 2015.

[17] Y. Cheng, S. Yaoqiao, X. Hongmin, and Z. Nan, “Millling force model prediction considering tool runout with three-teeth alternating disc cutter,” The International Journal of Advanced Manufacturing Technology, vol. 114, no. 11-12, pp. 3285–3299, 2021.

[18] B. Jiang, T. Zhang, P. Zhao, and J. Zhao, “Dynamic milling force model for a milling cutter under vibration,” International Journal of Advanced Manufacturing Technology, vol. 109, no. 5-6, pp. 1297–1317, 2020.

[19] H. Cao, Y. Song, B. Wu, K. Wang, and D. Qu, “A force model of high-speed dry milling CF/PEEK considering fiber distribution characteristics,” Journal of Manufacturing Processes, vol. 68, pp. 602–615, 2021.

[20] X. Jing, R. Lv, B. Song, J. Xu, S. H. I. Jaffery, and H. Li, “A novel run-out model based on spatial tool position for micro-milling force prediction,” Journal of Manufacturing Processes, vol. 68, pp. 739–749, 2021.

[21] Z. Hu, C. Qin, Z. Shi, Y. Tang, X. Zhang, and Y. Zou, “An effective thread milling force prediction model considering instantaneous cutting thickness based on the cylindrical thread milling simplified to side milling process,” The International Journal of Advanced Manufacturing Technology, vol. 110, no. 5-6, pp. 1275–1283, 2020.

[22] H. Qu, B. Geng, B. Chen et al., “Force perception and bone recognition of vertebral lamina milling by robot-assisted ultrasonic bone scalpel based on backpropagation neural network,” IEEE Access, vol. 9, p. 52101, 2021.

[23] H. Tanaka, M. Kitamura, Faculty of Science and Technology, Sophia University 7-1 Kio-cho, Chiyoda-ku, Tokyo 102–8554, Japan, and Department of Mechanical Engineering, Graduate School, Nagaoka University of Technology, Nagaoka, Japan, “Machinability of thermo-plastic-carbon fiber reinforced plastic in inclined planetary motion milling,” International Journal of Automation Technology, vol. 12, no. 5, pp. 750–759, 2018.

[24] G. Kiswanto, Y. R. J. Poly, Y. R. Johansen, and T. J. Ko, “Preliminary design of two dimensional vibration assisted machining system for multi-axis micro-milling application,” Key Engineering Materials, vol. 846, pp. 105–109, 2020.

[25] D. Ray, A. B. Puri, and Nagahanumaiah, “Investigation on cutting forces and surface finish in mechanical micro cutting of Zr-based bulk metallic glass,” Journal of Advanced Manufacturing Systems, vol. 18, no. 1, pp. 113–132, 2019.