ANALYSIS ON ROOT CUTTING MECHANISM OF SELF-PROPELLED CHINESE CABBAGE HARVESTER AND OPTIMISATION OF DEVICE PARAMETERS /
自走式大白菜收获机切根机理分析及装置参数优化

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ABSTRACT
For Chinese cabbage cutting device in the harvesting process, the problem of cutting resistance and low cutting root qualification rate will occur. This paper takes the Chinese cabbage root as the research object, analyses the root-cutting mechanism of Chinese cabbage, and determines that the main factors affecting its cutting effect are the cutter's inclination angle, rotational speed and its working speed. The finite element method is adopted to establish a rigid-flexible coupling model between the cutting device and the cabbage root, and the Response Surface Method (RSM) central composite design method is used to investigate the relationship among the cutter inclination angle, the cutter rotational speed as well as the working speed and Maximum root-cutting reaction force (MRF) of the cabbage and to further obtain the optimal combination of parameters. Field test results show that in the optimal combination of parameters, which means cutter inclination angle of 11°, cutter rotating speed of 216 r/min and working speed of 0.28 m/s, the root cutting effect is perfect. At this time, the root-cutting qualification rate of 92.81% and field productivity of 0.12 hm²/h, meet the requirements of the standard of Chinese cabbage harvesting mechanization. The results of the study can provide reference for optimization of Chinese cabbage harvesting equipment design.

摘 要
针对大白菜切割装置在收获过程中存在切割阻力大、切根合格率低的问题。本文以大白菜根部为研究对象，分析大白菜切根机理，确定影响其切割效果的主要因素为割刀倾角、割刀转速和工作速度。利用有限元法建立切割装置与大白菜根部刚柔耦合模型，采用响应面（RSM）中心复合设计方法，探究割刀倾角、割刀转速和工作速度与大白菜最大切根反作用力（MRF）影响关系，并获得最优参数组合。田间试验验证结果表明，在最优参数组合割刀倾角为 11°、割刀转速为 216r/min 和工作速度为 0.28m/s 时，切根效果较好，此时切根合格率为 92.81%，田间生产率为 0.12hm²/h，满足大白菜收获机械化标准的要求。研究结果为大白菜收获装备设计优化提供参考。

INTRODUCTION[1]

Originated in China, Chinese Cabbage is a cruciferous Brassica biennial herbaceous plant, with high yield per unit area, convenient storage, richness in nutritional value and other advantages [1]. The Chinese Cabbage, whose planting area has reached 1.8 million hm^2, accounting for 15% of the total vegetable planting area, has ranked the second largest vegetable in China [2]. With the increasing area of cabbage planting, traditional manual harvesting has been unable to meet the needs of cabbage industrialization [3]. Therefore, the research and development of Chinese cabbage mechanical harvesting equipment is of great significance to improve operational efficiency and promote the development of vegetable mechanization.

Scholars at home and abroad have carried out research on Chinese cabbage harvesting: Kanamitsu [4] and others developed a walk-behind self-propelled cabbage harvester, which realizes the combined harvesting of cabbage, focusing on the design of the root-cutting device and the extraction device, but when harvesting different varieties of cabbage, there are problems such as poor root-cutting effect and greater damage.

Yanmar and Osada Nouki company jointly developed a crawler self-propelled cabbage harvester, which realized the first extraction and backward conveying, and at the same time clamped the cut root during

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conveying to ensure the stability of the cut root, but the structure is complicated, the cost is high, and the requirements for planting mode are strict [5]. Kim et al developed a small crawler self-propelled cabbage harvester, which focuses on the optimization of extraction mechanism, and has a better extraction effect, but the damage rate of the plant is higher, and the adaptability is poor [6]. Yao Huiling of China Agricultural University designed a double screw plucking harvesting device to provide reference for the design and optimization of root cutting device, but no prototype was developed [7]. Zhao Tusen et al. of Heilongjiang University designed a two-row cabbage harvester, using the first extraction and then cut the root method, but the harvest cut loss rate is high, the performance needs to be improved [8]. In summary, the domestic and foreign cabbage harvester is mainly pulling first and then cut, although the pulling efficiency is high, but the plant damage is large and the demands for position of the root cutting and attitude are strict, at the same time there are problems including cutting operation resistance and low cabbage root-cutting qualification rate, which restrict the standardization of harvesting and planting of Chinese cabbage to improve the economic benefits. Therefore, there is an urgent need to study and develop cutting device with stable performance, and good root-cutting effect, which is meaningful to accelerate the development of mechanized cabbage harvesting.

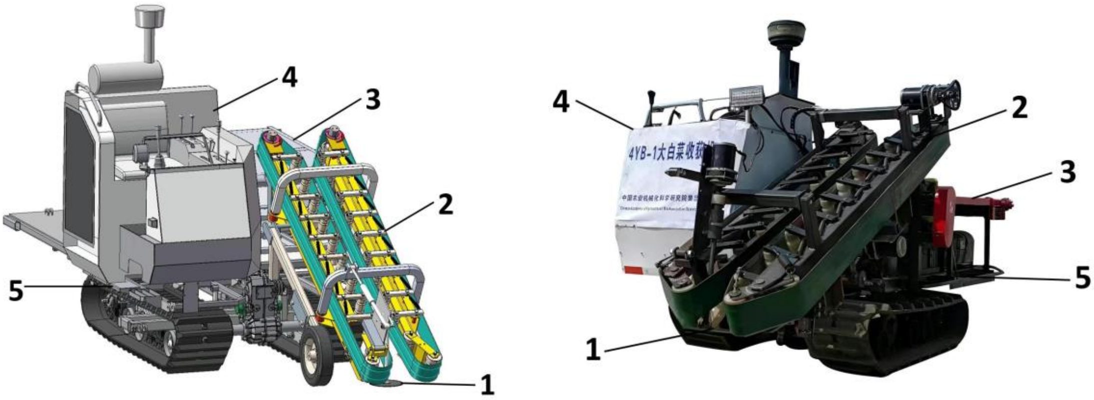
For the problem of large cutting resistance and low qualified rate of root cutting in the process of cabbage harvesting, this paper analyzes the main contributing factors affecting the cutting effect of cabbage root based on the mechanism of cabbage root cutting, uses the finite element method to establish a rigid-flexible coupling model of the cutting device and the root of the cabbage [9], and virtually simulates the process of cutting the root of the cabbage to seek for the optimal combination of the cutting device and obtains a better combination of the parameters of the cutting device through the verification of the field test.

MATERIALS AND METHODS

Structure design

- **Complete machine structure**

The whole structure of a crawler self-propelled Chinese Cabbage harvester is shown in Figure 1. Mainly composed of a cutting device, clamp conveying device, transverse conveying device, console, and automatic chassis, it can complete the root cutting, clamp transportation, transverse conveying, and manual basket loading at one time, to realize the joint harvesting of Chinese Cabbage. When running, its clamp conveying device is first adjusted by the console to incline 20°~30° from the ground. In that case, the ring cutter of the cutting device is tightly closed to the ground and aligned with the Chinese Cabbage. As the machine advances, the cutting device is driven by the motor to complete the root cutting of the Chinese Cabbage, and then the root-cut cabbage will be transported into the transverse conveying device at the top of the machine by the clamp conveying device. After that, cabbages will be selected and packaged artificially, which marks the completion of the harvest. The cutting device and clamp conveying device are designed to be adjustable to ensure that the machine can adapt to different situations. The main technical parameters of the harvesting machine are presented in Table 1.



(a) Three-dimensional diagram *(b) Actual diagram*

Fig. 1 - A crawler self-propelled Chinese Cabbage harvester

1. cutting device; 2. clamp conveying device; 3. transverse conveying device; 4. console; 5. self-propelled carrier

Table 1

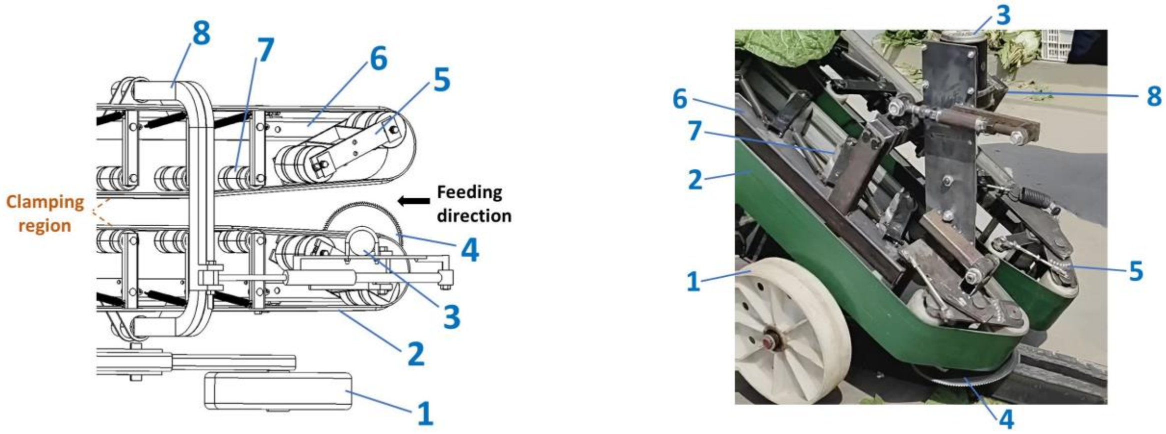
Technical characteristics of the crawler self-propelled Chinese Cabbage harvester

Parameter	Value

External dimensions(L×W×H) / m	4.1×2.0×2.3
Overall Weight / kg	1520
Auxiliary Power / kW	52
Walking Speed / m/s	0.2~1.8
No. of Rows Harvested / -	1
Appropriate Cabbage Ball Diameter / mm	150~200

- **Cutting device structure**

The cutting device is one of the key components of the Chinese cabbage harvester, as shown in Figure 2. It is designed to be placed at the front end of the clamp conveying device, mainly consisting of a profiling wheel, a follower pulley set, a front-end clamping belt, a drive motor, and a serrated disc cutter. The serrated disc cutter is mounted between the sets of driven wheels near the end of the profiling wheel, with the drive motor located at the top of it. The front clamping belt is powered by the motor of the conveyor unit, which can effectively clamp the cabbage and convey it upward through the follower pulley set and tensioner pulley. When the cutting device is aligned with the cabbage, the serrated disc cutting knife rotates at high speed in the opposite direction, in collection with the follower pulley set and the front clamping belt to complete the root-cutting of the Chinese Cabbage. The inclination, rotating speed, and front clamping angle of the serrated disc cutter are all adjustable to match different working environments, thus improving the adaptability and operability of the machine.



（a）Structure of the Cutting Device *（b）Actual diagram of the Cutting Device*

Fig. 2 - Cutting Device

1.Profiling wheel; 2. Front-end clamping belt; 3. Drive motor; 4. The serrated disc cutter; 5.Follower pulley set; 6. Rackmount; 7. Tensioner pulley; 8. Joint beam.

Analysis of root cutting mechanism

The cutting device is powered by a servo motor, as shown in Figure 3a. Analyzed from the starting point of the cut, the cabbage root is subjected to the *X*, *Y*, and *Z* direction of the cutting force of F_1, F_2, and F_3, respectively; The projection components of F_1 and F_3 in the *XY* plane are F_{1xy} and F_{3xy}, respectively; the projection components of F_{1xy} in the *X*-axis and *Y*-axis are F_{1x} and F_{1y}, respectively; the projection components of F_{3xy} in the *X*-axis and *Y*-axis are F_{3x} and F_{3y}, respectively; θ is the angle between F_{1xy} and the force F_1; γ is the angle between F_{3xy} and F_3; β and φ are the angles of the projected components F_{1xy} and F_{3xy}, respectively, concerning the *X*-axis direction. Due to the inclination angle of the cutting disc cutter and the disc cutter serrations, there still exists a certain cutting force in the *X*-axis and *Z*-axis directions (F_2). The X-axis direction is subjected to two opposite directions of the cutting force F_{1x} and F_{3x}, and their value of them is so high that the cutting disc cutter is seriously worn. Under the joint action of the cutting friction in the forward direction and the component cutting forces F_{1z} and F_{3z} in the Z-axis direction, the cabbage can be subjected to a large longitudinal component force, which helps to extract the roots of the cabbage. Setting the actual operation situation γ to zero [*10]* only the effect of pitch angle θ is taken into consideration. For the angle of θ is adjustable, it will help to find the optimal cutting combination parameters.

When working, the serrated mouth on the edge of the serrated disc cutter will clamp and shear the cabbage root [11], and the related process is shown in Figure 3b.

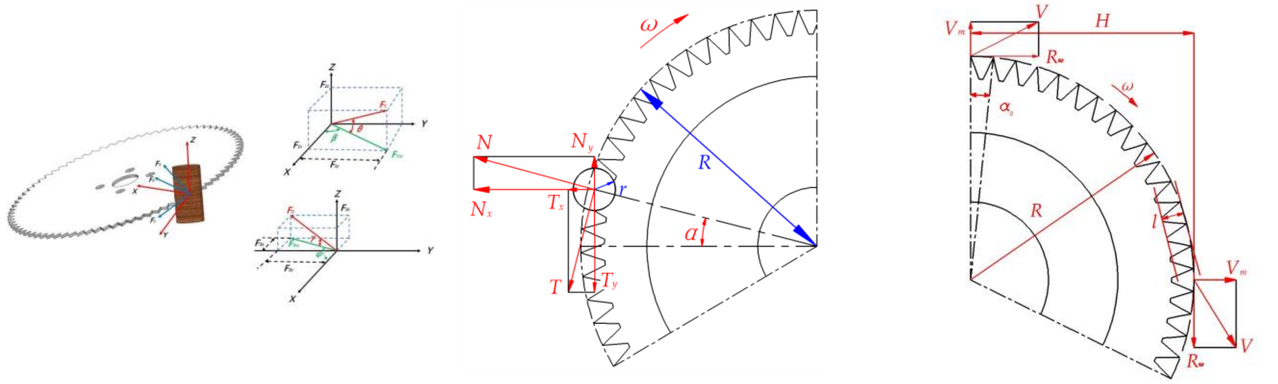


Fig. 3 - Root cutting mechanism analysis diagram

(a) Spatial analysis of root-cutting force; (b) Force Analysis Diagram of the Cut-root when cut; (c)The Analysis of Disc Cutter Motion

During the root-cutting process, if analyzing from the starting point of root cutting, it suggests that the cabbage root is subjected to cutting force F_X and clamping force F_Y, which is:

$$\begin{cases} F_X = T_X + N_X \\ F_Y = T_Y - N_Y \end{cases} \tag{1}$$

where:

N is the normal reaction force on the disc cutter during the cutting process, (N);

N_X is the component forces in the *X* directions, (N);

N_Y is the component forces in the *Y* directions, (N);

T is the friction force on the serrated disc cutter during the cutting process, (N);

T_X is the component forces in the *X* directions, (N);

T_Y is the component forces in the *Y* directions, (N).

The conditions under which the serrated disc cutter can clamp on the roots of the cabbage are [12]:

$$F_Y > 0 \tag{2}$$

It can be referred that $TY>NY$, and $F=Nf$, which means:

$$N \cdot f \cos\alpha > N \cdot \sin\alpha \tag{3}$$

At this time, when $f>\tan\alpha$, the serrated disc cutter can clamp well:

$$\alpha = \arccos\frac{R}{R+r} \tag{4}$$

where:

R is the radius of the serrated disc cutter, (mm);

r is the radius of the cabbage root, (mm);

f is the friction between the cutting disc cutter and the cabbage root, generally taking 0.4~0.7;

α is the angle between the cutting disc cutter and the X-axis for the reaction force on the cabbage root, (°).

To ensure that the cabbage root can be cut off smoothly, the working area of the cutting device should be larger than the width of the cabbage ridge. Inside the working area, the direction of the combined speed of the forward speed of the cabbage harvester is opposite to the direction of the absolute speed of the cutting disk knife, and the absolute speed component of the forward direction of the machine should not be less than the forward speed of the machine. The working area of the cutting device and the analysis of the disc cutter motion are shown in Figure 3c. Therefore, the width of the working area of the cutting device is calculated as:

$$\begin{cases} H \le 2R(1-\sin\alpha_0) \\ \sin\alpha_0 = \dfrac{30v_{\max}}{\pi Rn} \end{cases} \tag{5}$$

where:

H is the working width of the disc cutter, (mm);

R is the radius of the disc cutter, (mm);

v_{max} is the maximum working speed of the machine, (m/s);

α_0 is the horizontal angle of the cutter relative to the forward direction of the machine, (°);

n is the rotational speed of the disc cutter, (r/min).

To keep the working disc cutter away from the adjacent rows of cabbage, the trajectory of the cutter teeth's top center should be separated from the adjacent rows of cabbage for a certain distance, the expression is:

$$S \geq 2R + \Delta l + \frac{d_c}{2} \tag{6}$$

where:

S is the row spacing of cabbage planting, (mm);

R is the radius of the disc cutter, (mm);

Δl is the spacing between the movement track of tooth top center and the adjacent rows of cabbage, (mm);

d_c stands for the middle diameter of cabbage, (mm).

According to the actual measurement and reference to literature related to cabbage and sugar cane cutting [13] [14], Δl is taken as 100 mm, d_c (the average diameter of cabbage) is 200 mm, and cabbage planting row spacing is 450 mm, so as to determine R (the radius of the disc cutter) should not be longer than 125 mm. Considering that the cutter is installed with the ground into a certain angle of inclination, the range of R values can be appropriately increased. Studies on root-cutting of vegetables, such as Chinese broccoli, suggest that as the rotating speed increases, the more unstable the cutter is, the more vibration there will be [12]. Therefore, to ensure the quality of root cutting, a low rotational speed of root cutting is often chosen. Bringing R into the cutting device working area width calculation formula, taking v_m max as 1.6 m/s, n (disc cutter maximum speed) as 400 r/min, at this time the calculation of H (the working area width) is no more than 0.14 m.

However, to avoid disc cutter leakage, S_m (disc cutter's leading distance) must be less than or equal to l (the cutter's working distance); at the same time to ensure the root of the cabbage must be completely cut off, l must be greater than or equal to the maximum diameter of the cabbage root d_{max}, then the expression is:

$$\begin{cases} S_m \leq l \\ S_m = \dfrac{60v_m}{Zn} \\ l \geq d_{\max} \end{cases} \tag{7}$$

where:

S_m is the disc cutter's leading distance, (m);

l is the maximum working distance of the disc cutter, (m);

v_m is the working speed of the machine, (m/s);

Z is the number of teeth of the disc cutter, (piece);

n is the rotational speed of the disc cutter, (r/min);

d_{max} is the maximum diameter of the cabbage root, (m).

The serrated cutting disc cutter is equipped with several continuous serrations, and in theory, the more teeth are, the root cutting process can be approximately continuous cutting. According to the cabbage physical parameters of the test, the maximum diameter of the cabbage root d_{max} value is taken as 30 mm, which is regarded as the minimum working distance of the disc cutter. Based on the design requirements of the cabbage harvester, v_m should be 1.2 m/s when it can work smoothly; Z (the maximum number of teeth) is 80 when R (the radius of the disc cutter) is taken as 125 mm. Taking them into account, n (the rotating speed of the disc cutter) should be no less than 30 r/min without cut missing and its value range is 30 up to 400 r/min.

In summary, the stability of root-cutting can be ensured by adjusting appropriate working parameters through the design of reasonable cutting disc cutter structure parameters. From equation (5), the main factors affecting the stability of root cutting can be confirmed: cutter inclination angle, cutter rotating speed, and forward speed. Combined with the relevant literature and the analysis of principle, the structural parameters of the cutting disc cutter and other data are preliminarily determined: the diameter of the cutting disc cutter is 250 mm, the thickness is 3 mm, the material is 65Mn, the inclination angle of the cutter is 5^{o}~15^{o}, the rotational speed of the cutter is 100~300 r/min, and the forward speed is 0.2~0.4 m/s. The above structural and working parameters will be verified in the simulation test and will be further verified through the field test.

Design of Cabbage Root-cutting Simulation Experiment

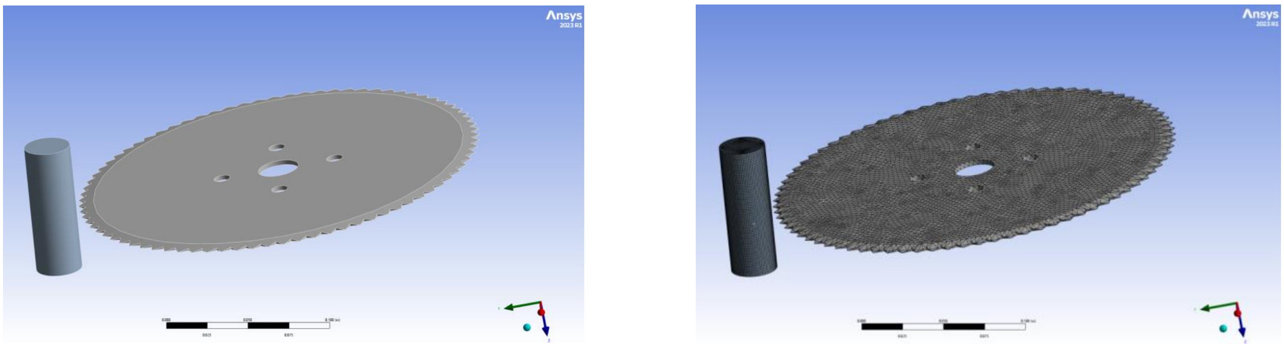
Based on ANSYS/LS-DYNA, a rigid-flexible coupling model related to the interaction between the cabbage root and the cutting disc cutter was constructed. The cabbage root was assigned the soft body characteristics while the cutter was assigned the rigid body characteristics [15]. The optimal combination parameters of the cutting device are obtained through dynamic analysis by performing simulation tests and parameter optimization by the central composite design method of response surface (RSM), which can be used for the study of cabbage harvesting prototype field trials.

- **Modeling of Cabbage Roots and Cutting Disc Cutter**

Cabbage roots are divided into main roots and lateral roots, and the main roots also have different lengths and diameters. To simplify, the site where the upper part of the underground root of the soil combines with the foliar root immediately above it is selected as the cutting part in this study. In this part, the root structure has a fibrous layer outside and a matrix inside. For simulation and calculation, the cabbage root model was designated as a solid cylinder and the material was considered homogeneous. According to the mechanical properties of cabbage roots, due to the existence of fibers along the axial direction, the mechanical properties of the material along the axial and radial directions of the root are quite different, while the mechanical properties are consistent along the radial direction and in all directions in the plane where they are located, hence they can be regarded as linearly elastic radially isotropic materials [16], ignoring micro-defects and micro-discontinuities [17].

Based on the previous physical measurements of the cabbage root, the average diameter of the root is 28.78 mm and the average length is 103.76 mm. In this chapter, the model of the cabbage root is regarded as a cylinder with a diameter of 28 mm and a length of 80 mm, and the cutting disc cutter is modeled with a diameter of 250 mm, a thickness of 3 mm, and an army of teeth of 80 as shown in Figure 4a.

Since only meshes and nodes can be computed and analyzed when performing finite element analysis, meshing the cabbage root and the cutting disc cutter is needed. A slightly coarser mesh size can be selected to shorten the calculation time and reduce the analysis effort. After the division, the cabbage root became a hexahedral cell, the number of its grid is 78,489, and the number of cells is 73,920; cutting the disc cutter the tetrahedral cell, the number of its grid is 90,724, the number of cells is 114,436. Figure 4b shows the effect of cutting the model after meshing.



(a) Geometric model of cabbage root and cutting disc cutter *(b) Cutting model effect after mesh division*

Fig. 4 - Modelling diagram

- **Setting of model material properties**

Through the above analysis, the cabbage root is a typical anisotropic material, hence being set up as a flexible body. According to the material model provided by ANSYS/LS-DYNA, orthotropic linear-elastic orthotropic anisotropic materials adapt for modeling Chinese cabbage root materials.

Thus, by adding failure parameters to the file, the root material model can be disabled and can be used to simulate the root-cutting process [18]. The model material parameters of Chinese cabbage root include density DENS, Poisson's ratio uXY, Poisson's ratio uXZ (uYZ), radial modulus of elasticity Ex (Ey) or axial modulus of elasticity Ez, radial shear modulus Gxz (Gyz), and axial shear modulus Gxy. Based on the tests of the mechanical properties of Chinese cabbage root and the reference to the related literature [8] [19] , it was determined that the material parameters of the Chinese cabbage root were as shown in Table 2.

Table 2

The material parameters of the cabbage root model

Parameter	Value
DENS / kg·m^{-3}	880
uXY	0.06
uXZ	0.30
uYZ	0.30
Ex / MPa	398
Ey / MPa	398
Ez / MPa	140
Gxz / MPa	29.7
Gyz / MPa	29.7
Gxy / MPa	15.3

The cutting disk cutter is set as a rigid body, which will not be deformed during the simulation process and the strength and hardness of it is much larger than that of the cabbage root. To reduce the amount of calculation to shorten the simulation time, the material of the cutting disc cutter is 65Mn. The cutter takes 65Mn, a rigid body material for reference, whose density is 7.85 × 103 kg/m^3, modulus of elasticity is 210 GPa, Young's modulus is 2 × 10^5 MPa, and the Poisson's ratio is 0.3 [20].

The cabbage root and the disk cutter interact with each other, and the contact type is friction. Due to the destruction of the cabbage root material during the cutting process, the contact characteristics are set to "erosion", i.e., the face-to-face erosion contact algorithm ESTS. The dynamic and static friction coefficients of the defined contact surfaces are 0.15 and 0.23 respectively. Since the Chinese cabbage is clamped by the front-end gripping device at the moment of root-cutting, the fixed constraints are added at the upper end of the root to achieve the real effect. The cutting disc cutter is adjusted to rotate around the Z-axis to move along the X-axis, and the angle between the disc cutter and the horizontal forward direction is adjusted, i.e., the direction of movement of the cut root.

- **Response Surface Experimental Designs**

During the harvesting process of Chinese cabbage, the cabbage root is affected by the soil and the cutting device. Combined with the results of the stress analysis of the cabbage root, the MRF directly affects the damage of the cabbage and acts as an important index to measure the effect of cabbage harvesting. Based on the theoretical analysis, the cutter inclination angle, cutter rotational speed, and machine forwarding speed were selected as the test factors, which were expressed as X_1, X_2, and X_3 respectively. MRF was chosen as the test index, denoted by y. To adapt to different working conditions and soil types, the value range of α was determined to be 5°~15° regarding the range of commonly used cutting angles [10].

Based on the preliminary test and theoretical analysis, the rotational speed of the serrated disc cutter was selected to be 100~300 r/min, and the forward speed of the machine was selected to be 0.2~0.4 m/s. Response surface testing was performed by using a centralized composite design method.

The factor and level coding is shown in Table 3.

Table 3

Code	Experimental factors		
	Cutter Inclination Angle X_1/(°)	Cutter Rotational Speed X_2/(r/min)	Machine Forwarding Speed X_3/(m/s)
-1.682	1.6	32	0.13
-1	5	100	0.2
0	10	200	0.3
1	15	300	0.4
1.682	18.4	368	0.47

Test Equipment and Methods

- **Experimental Arrangement**

On March 29th, 2023, the developed 4YB-1 cabbage harvester prototype, in Shandong Dezhou Yucheng Vegetable Professional Cooperative cabbage planting base, was used to carry out field trials on the test cabbage varieties Significant ("Si Jin" in Chinese). Rows of multi-row open-air planting were adopted, the soil type was clay, the top of the row width was 500~550 mm, plant spacing was 390~430 mm and row spacing of 800~850 mm. The soil type was clay soil, the width of the top of the row was 500~550 mm, and the plant spacing was 390~430 mm. Row spacing was 800~850mm, and the cabbage was elliptical, with an average height of 380 mm. The ball diameter was about 170 mm, and the total weight of a single cabbage was an average of about 2.3 kg, with a root diameter of about 31 mm and a root length of about 90 mm.

The test randomly selected five rows of cabbage with basically the same growth condition and 20 m as the test area with a total of five replicated tests. According to the optimization results of the root-cutting simulation test, the structural parameters and working parameters of the cutting device of the cabbage harvester were pre-adjusted before the test, and after the devices of the prototype were stabilized, the cabbage root-cutting and harvesting test were conducted.

- **Evaluation Indicators**

Due to the lack of relevant standards and specifications for mechanized harvesting of cabbage, this experiment refers to the relevant test methods of Test Methods for Sugar Beet Harvesting Machinery (JB/T 6276-2007) and Specification for Production of Knotty Kale (GB/Z 26582-2011) as well as the operational standards. Taking the field productivity and root-cutting qualification rate as the mechanical performance of the cabbage harvester-cutting device, indexes are evaluated. Each index is defined as follows:

Field productivity refers to the actual harvested area completed by the cabbage harvester per unit of time. The actual operating width is estimated in terms of the row spacing of the cabbage, and the expression:

$$E = 3.6Bv \tag{8}$$

where:

E is the field productivity, (hm^2/h);

B is the operating width of the cabbage harvester, (m);

v is the operating speed of the cabbage harvester, (m/s).

Root-cutting qualification rate refers to the proportion of the total number of harvested cabbages that have passed root-cutting. The evaluation criteria for qualified root cutting are that the location of cut root should locate in a better area and the cutting device should not cause damage to the cabbage bulb, etc., and its expression is:

$$Q_c = \frac{N_c}{N} \times 100 \tag{9}$$

where:

Q_c is the qualified rate of root cutting, (%);

N_c is the number of qualified cabbages with cut roots, (tree);

N is the total number of harvested cabbages, (tree).

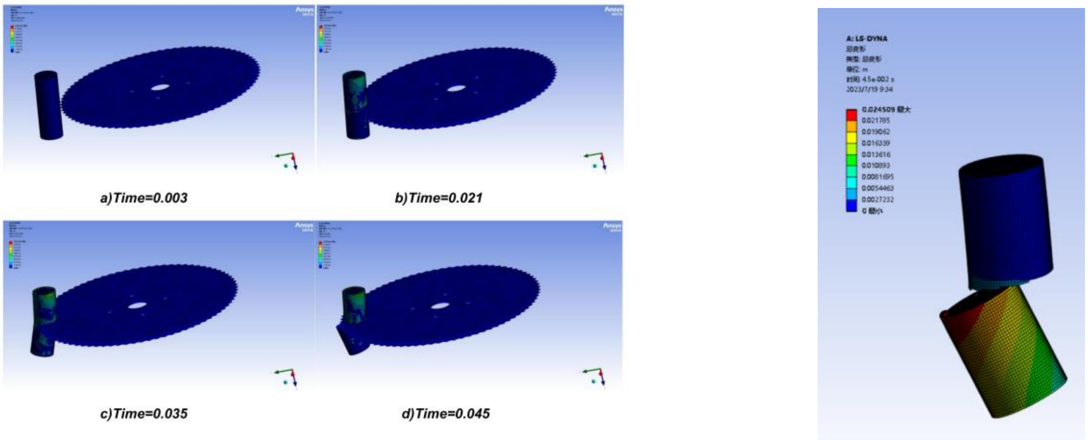
RESULTS AND DISCUSSION

Cutting Simulation Modeling Process and Results

- **Cutting Simulation Modeling Process**

The factors and levels are designed according to the central composite design method of response surface (RSM), and each parameter of each group of root-cutting models is set separately for simulation and calculation of results. The stress cloud displacement process of the cutting simulation is obtained by reading the resultant file calculated by the LS-DYNA program as shown in Figure 5a.

The total simulation time is set to 0.045 s, the inclination angle of the cutting disk cutter and the horizontal forwarding direction is 5^{o}, and the rotational speed and horizontal speed are set to 300 r/min and 0.4 m/s respectively. It can be seen from the pictures that the disc cutter cuts into the Chinese cabbage root in the time of 0~0.021 s, but the root does not fracture; in the time of 0.035 s, the disk cutter continues to cut, and the root of Chinese cabbage began to fracture, until 0.045 s, the cabbage root completely fractured. The final orthogonal test results are shown in Table 4. The root fracture model is shown in Figure 5b, with the red part representing the maximum stress on the cabbage root.



(a) Simulation process of root-cutting cloud displacement map *(b) Total deformations of cabbage roots*

Fig. 5 - Simulation of root cutting process

Table 4

Orthogonal test results of root-cutting models

Serial number	Experimental factors			Y / N
	X_1 / (°)	X_2 / (r/min)	X_3 / (m/s)	
1	10	368	0.3	213.22
2	5	100	0.4	214.55
3	10	200	0.3	100.44
4	5	300	0.4	176.76
5	18.4	200	0.3	147.95
6	10	200	0.3	99.91
7	10	200	0.3	109.32
8	10	200	0.3	98.34
9	15	300	0.4	158.53
10	15	100	0.2	175.34
11	10	200	0.3	96.56
12	5	100	0.2	192.94
13	10	200	0.47	191.16
14	10	200	0.13	146.14
15	10	200	0.3	110.62
16	5	300	0.2	171.36
17	15	100	0.4	219.82
18	15	300	0.2	159.21
19	1.6	200	0.3	183.96
20	10	32	0.3	255.49

The MRF variation curve for the root-cutting process is shown in Figure 6, with the first peak due to the initial contact of the disk cutter with the root. The maximum peak occurs between 0.030 s and 0.035 s when the disk cutter cuts the deepest part of the root and its multiple teeth are in contact.

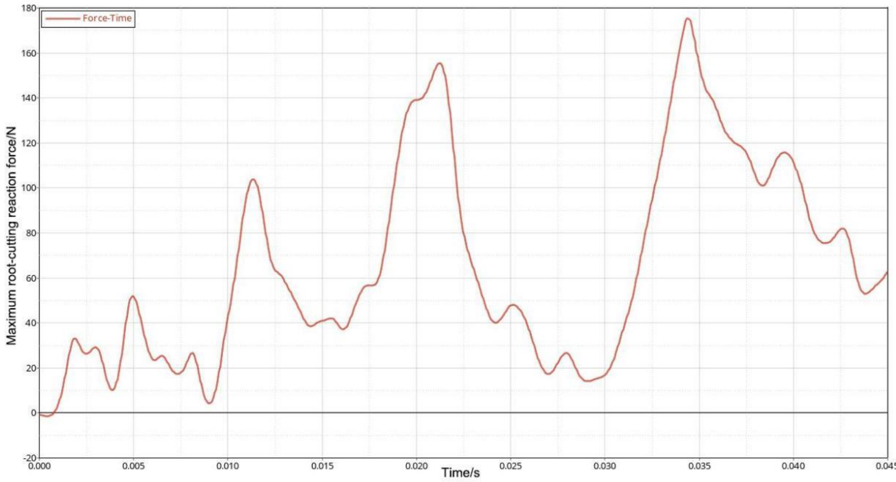


Fig. 6 - Plot of MRF variation during root-cutting simulation

- **Establishment of the regression equation and variance analysis**

The multivariate regression analysis and fitting of the experimental results using Design-Expert 12 software yielded the multivariate regression quadratic equations for the cutter inclination, cutter rotational speed, forward speed, and MRF:

$$\begin{aligned} Y_1 = 102.90 - 7.56X_1 - 15.22X_2 + 10.73X_3 - 2.26X_1X_2 \\ + 2.10X_1X_3 - 7.67X_2X_3 + 20.02X_1^2 + 44.21X_2^2 + 20.98X_3^2 \end{aligned} \tag{10}$$

The analysis of variance (ANOVA) is shown in Table 5. A P-value of the MRF y model is less than 0.0001, indicating the validity of this model. The p-values of the cutter inclination X_1, cutter rotation speed X_2, and forward speed X_3 on MRF are less than 0.05, suggesting that X_1, X_2, and X_3 have a significant effect on MRF. From the F-value, it can be seen that the magnitude of the effect of X_1, X_2, and X_3 of the clamped carrier on MRF is X_2, X_3, and X_1 in that order.

Table 5

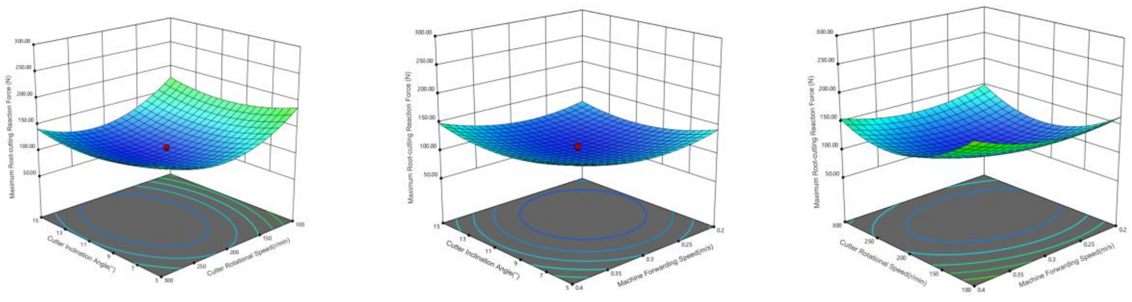
The analysis results of variance (ANOVA)

Source	Maximum Root-cutting Reaction Force / N			
	Sum of squares	Mean square	F	p
Model	41162.98	4573.66	49.42	< 0.0001
X_1	780.92	780.92	8.44	0.0157
X_2	3164.26	3164.26	34.19	0.0002
X_3	1572.06	1572.06	16.99	0.0021
X_1X_2	40.73	40.73	0.4400	0.5221
X_1X_3	35.24	35.24	0.3807	0.5510
X_2X_3	470.78	470.78	5.09	0.0477
X_1^2	5777.93	5777.93	62.43	< 0.0001
X_2^2	28162.52	28162.52	304.28	< 0.0001
X_3^2	6340.91	6340.91	68.51	< 0.0001
Residual error	925.55	92.55		
Misfit term	749.56	149.91	4.26	0.0689
Pure error	175.98	35.20		
Total difference	42088.53			

- **Analysis of the influence law of interaction terms on test indexes**

The response surface is shown in Figure 7. From Fig. 7a, when the forward speed X_3 is the center level, i.e., X_3=0.3 m/s, it can be seen that the MRF decreases and then increases with the increase of X_1 and X_2.

From Fig. 7b, it can be seen that when the cutter speed X_2 is the center level, i.e., X_2=200 r/min, the interaction between X_1 and X_3 is relatively smooth, which indicates that X_1 and X_3 have the least influence among the interaction factors. From Fig. 7c, it can be seen that when the cutter inclination X_1 is center level, i.e., $X_1=10^o$, the value of MRF decreases and then increases with the increase of X_2; and with the decrease of X_3, the MRF also decreases gradually.



(a) (b) (c)

Fig. 7 - Influence response surface of test factors on test indexes

- **Optimization of parameters**

The minimum value of the maximum root-cutting reaction force (MRF) of the cabbage root is selected as the optimization objective, and the objective function expression is as follows:

$$\begin{cases} \min Y(X_1, X_2, X_3) \\ 5^o \le X_1 \le 15^o \\ 100r/\min \le X_2 \le 300r/\min \\ 0.2m/s \le X_3 \le 0.4m/s \end{cases} \tag{11}$$

According to the optimization calculation results of DesignExpert software, the minimum value of MRF was 99.636 N. At this time, the optimal parameter combinations were a cutter inclination angle of 11.055^o, cutter rotational speed of 215.669 r/min, and working speed of 0.276 m/s. Considering the cost of the optimized parameter combinations and the feasibility of the field test, the above values were rounded up to the closest integer, which was 11^o, 216 r/min, and 0.28 m/s respectively. Validation tests were conducted based on the optimized cutting device and the optimum MRF was determined to be 102.785 N, which was comparable to the original values within an acceptable percentage range (3.16%). The optimal parameter combinations optimized by the root-cutting simulation test set the basis for subsequent field tests of the prototype.

Cutting device field test results

Before the test, the optimal combination of parameters was selected, the forward speed of the prototype was adjusted to 0.28 m/s, and the rotational speed of the cutting disc cutter was adjusted to 216 r/min and adjusted to an angle of 11^o with the ground to verify the results of the root-cutting simulation test. Field tests show that the overall performance of the prototype is stable, the cutting device works smoothly, the overall damage to the cabbage plant is little, and the prototype has a high degree of harvest integrity which meets the requirements of single-row cabbage harvest (Figure 8), the average field productivity of the cabbage harvester is about 0.12 hm^2/h. In the cabbage-cutting process, due to soil unevenness, the prototype is easy to harvest inaccurately, it needs the driver to correct, resulting in a reduction in the qualified rate of cut roots. However, the overall qualification rate is still high, the average value is about 92.81%.

There is no leakage of cuts, which verifies the reliability of the design of the cutting device, and further explains the importance of the cutting device in the mechanized harvesting of Chinese cabbage operations.

Fig. 8 - Harvesting Process and Cutting Effect of the 4YB-1 Cabbage Harvester Prototype in the Field

Discussion

In this study, the effects of cutter inclination angle, cutter speed, and forward speed on MRF were analyzed by dynamic simulation of root cutting. The MRF was minimal when the cutter inclination angle, the cutter speed, and the forward speed were 11^{o}, 216 r/min, 0.28 m/s respectively. At the same time, a high root-cutting qualification rate could be obtained in the field test. The effects of blade thickness, blade shape, and cutting position on MRF will be further studied in the future.

From the field test, it was found that due to the uneven soil, the prototype was not aligned when harvesting, and there were cases of incomplete cutting of roots or cutting damage to the cabbage, resulting in a decrease in the qualification rate of root cutting. As the cabbage is affected by the interaction of plant, soil, and cutting device in the actual process, the possible vibration of the cabbage plant during harvesting and the complexity of soil conditions also could affect the interaction during the root-cutting process. In the root-cutting simulation test, the soil and cabbage vibration in the cutting process was not considered, so there are some limitations. Therefore, it can be considered to further study the complex simulation model of cabbage plant-soil-cutting device interaction mutual influence, improving the reliability of the cutting device.

CONCLUSIONS

Based on the cabbage root cutting mechanism, this paper analyzes the main factors affecting the root cutting effect of cabbage and optimizes the parameters of the cutting device by using the central composite design method of finite element method and Response Surface Method (RSM). This device of cutter inclination angle and cutter speed is adjustable. The optimized cutting device effectively reduces cabbage root cutting resistance and improves cabbage field productivity and root cutting qualification rate. The main research conclusions are as follows:

(1) The optimized parameter combination of the cutting device is the key to lower resistance and damage on Chinese cabbage. Through the analysis of the root-cutting process and the construction of the cabbage root-cutting model, the cutter inclination angle, cutter rotational speed, and machine forward speed were identified as the key factors affecting the maximum root-cutting reaction force (MRF) of the cabbage.

(2) According to the key parameters of the cabbage and the cutting device, the dynamic simulation model of the cabbage root-disc cutting knife was established. Through the virtual simulation test of the cabbage root-cutting process, the multiple regression equations of the influence of the inclination angle, the rotational speed, and the forward speed of the cutter on the MRF were obtained. The degree of influence of each factor on MRF was determined, which was the cutter rotational speed, forward speed, and cutter inclination angle in descending order. The optimal combination of cutting device parameters was determined by using Design-Expert 12 software: when the cutter inclination angle was 11.055^{o}, the cutter rotational speed was 215.669 r/min, and the working speed was 0.276 m/s, the MRF was 99.636N. According to the feasibility of the optimal parameters verified by the field test, the rounded-up parameters 11^{o}, 216 r/min and 0.28 m/s were determined to further validate the optimized cutting device and working parameters. Based on the optimized parameter verification test, the optimum MRF was measured as 102.785 N, which is comparable to the original value within the acceptable percentage range (3.16%).

(3) Through the field test, the cutting device was verified in the optimal combination of cutting root parameters under the cabbage harvesting effect. The test results show that the field productivity of the cabbage harvester is 0.12 hm^2/h, and the qualified rate of root cutting is 92.81%, which meets the requirements of mechanized cabbage harvesting.

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