

DESIGN AND TESTING OF MODERN APPLE ORCHARD PRUNING MACHINERY

/ 现代苹果园修剪机械的设计与试验

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ABSTRACT

In response to the problems of low efficiency and difficulty of pruning operations in modern dwarf dense orchards, an adjustable position saw blade pruning machine was designed, mainly consisting of a pruning device, a regulating device and a hydraulic system. Through the mechanical and modal analysis of the circular saw blade, the limit speed of the circular saw blade was derived. A finite element model of the sawing process was established, and a single-factor simulation analysis was conducted for three important parameters: feed rate, circular saw blade speed and branch diameter, and a three-factor, three-level quadratic regression orthogonal test was designed to derive the best matching sawing parameters, which was verified in field tests. The test results showed that the average passing rate was 92.8% at the feed rate of 4 km/h under the circular saw blade speed of 2800 rpm, which was higher than 88.8% at 3 km/h and 88.9% at 5 km/h. The optimum sawing parameters were: the circular saw blade speed of 2800 rpm and feed rate of 4 km/h, which were consistent with the simulation results, and the passing rate of the cut was high at this time, meeting the technical requirements of orchard pruning.

摘要

针对现代矮砧密植果园修剪作业效率低、操作难度大等问题，设计了一种姿态可调节的锯片式修剪机械，主要由修剪装置、调节装置和液压系统组成。通过圆锯片的力学和模态分析，得出圆锯片极限转速。建立锯切过程的有限元模型，对进给速度、圆锯片转速和枝条直径三个重要参数进行单因素仿真分析，以此设计三因素三水平的二次回归正交试验，得出配合最佳的锯切参数，并进行田间试验验证。试验结果表明：在圆锯片转速2800rpm的情况下，进给速度4km/h时的平均合格率为92.8%，高于3km/h时的88.8%和5km/h的88.9%，得出配合最佳的锯切参数为：圆锯片转速2800rpm，进给速度4km/h，与仿真结果一致，此时切口的合格率高，满足果园修剪的技术要求。

INTRODUCTION

At present, the planting area and production of apples in China are among the highest in the world (Zheng et al., 2020; Zhang et al., 2021), and with the increasing area of orchard planting, the traditional planting methods can no longer meet the requirements of apple farming industry. For this reason, China had started to adopt the dwarf anvil dense planting method to improve the yield and quality of apples, which has the advantages of fast fruiting, high yield, high fruit quality and easy management (Shi L., 2018).

For various orchard pruning machines, scholars at home and abroad had conducted a lot of research. Shu Yu et al. designed a sawing apple pruner with a clamping mechanism, which added a clamping mechanism to the traditional sawing method to improve the stability of the cutting process (Shu Y. et al., 2018). Wang Zheng et al. conducted a kinetic simulation analysis and experiment on the sawing process of apple trees to study the mechanism of the effect of saw blade speed, work-in speed and branch diameter on the quality of the cut (Wang Z. et al., 2017). Zhang Jiayi et al. designed a single motor reciprocating grape pruner, which was driven by a single hydraulic motor and can prune the branches on one side and the top of the grape at the same time (Zhang J. X. et al., 2021).

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Liu Xuechuan et al. designed a combined profiling pruner, which can be adjusted according to different tree shapes, with high applicability and reduced pruning costs (Liu X.C. et al., 2020). Meng Y et al. analysed the sawing force magnitude of a small mulberry cutter under different sawing parameters based on orthogonal tests. The optimum sawing parameters were obtained (Meng Y. et al., 2019). At present, most apple orchards in China are still pruned manually or with simple machinery, which has problems such as high operation technology requirements, low automation and low pruning efficiency, and the traditional pruning methods such as heavy pruning, strong tree shaping and short cutting are not suitable for modern dwarf dense orchards.

In response to the above problems, this paper designed a saw blade apple tree pruning machine to meet the pruning requirements of dwarf dense orchards with high spindle shape. The design of the pruning device and adjusting device was analysed according to the tree shape of the dense apple orchard, and the final size was determined by constructing a mathematical model; mechanical and dynamics analysis and orthogonal test were conducted to determine the best-fit sawing parameters, and field performance test was carried out to realize the efficient pruning operation of dwarf dense apple orchards.

MATERIALS AND METHODS

Structure and working mechanism

In order to meet the requirements of simultaneous pruning of unilateral and top branches, a saw blade pruning machine was designed, as shown in Fig 1.

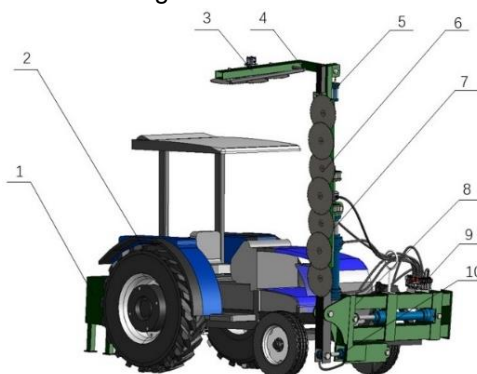


Fig. 1 - Schematic diagram of the trimming machine

1 - Hydraulic Station; 2 - Tractors; 3 - Horizontal trimming device; 4 - Automatic obstacle avoidance device; 5 - Horizontal angle adjustment device; 6 - Vertical trimming device; 7 - Vertical expansion device; 8 - Solenoid Valve; 9 - Vertical angle adjustment device; 10 - Horizontal expansion device

The working principle of the pruning machinery is: the circular saw blade is driven by the hydraulic motor to rotate at high speed, and the circular saw blade is driven by the synchronous belt to realize the staggered distribution of saw blades rotating in the same direction; the adjustment device is controlled by solenoid valve to carry out tilting and telescoping action to realize the pruning of apple trees of different shapes; the pruning machinery is installed in the front of the tractor, and the tractor provides the power to work

The trimming device mainly includes the horizontal trimming device and the vertical trimming device. Vertical trimming device uses a hydraulic motor to drive seven staggered circular saw blades, relying on a timing belt drive, to complete the vertical section trimming operation, with a required effective working length of 2200mm, as shown in Fig 2.

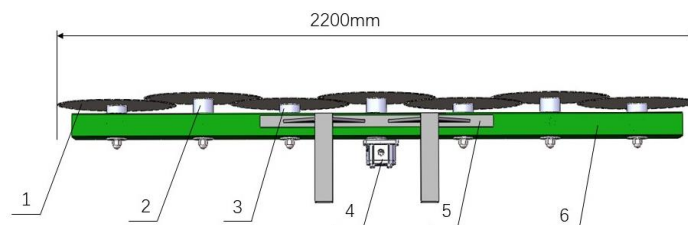


Fig. 2 - Vertical trimming device

1 - Circular saw blades; 2 - Long saw blade holder; 3 - Short saw blade holders; 4 - Hydraulic Motor; 5 - Saw base hook up square steel; 6 - Saw base support square tube;

The number of circular saw blades of the horizontal trimming device is three, and the working principle is the same as that of the vertical section, requiring an effective working length of 1000 mm and installing gas springs for obstacle avoidance, as shown in Fig. 3.

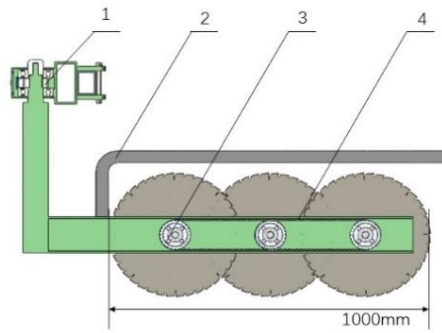


Fig. 3 - Horizontal trimming device

1 - Connecting gear; 2 - Automatic obstacle avoidance device; 3 - Timing pulleys; 4 - Synchronous belts

The adjustment device includes horizontal angle adjustment device, horizontal telescopic adjustment device, vertical angle adjustment device and vertical telescopic adjustment device, as shown in Fig 4. Each adjusting device controls the hydraulic cylinder through a solenoid valve to achieve adjustment.

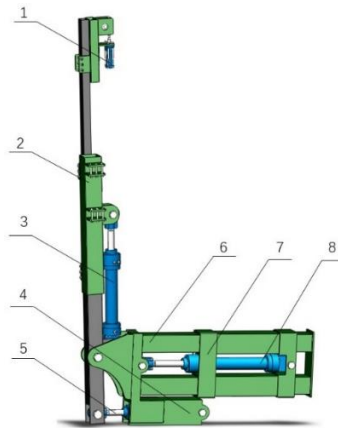


Fig.4 - Adjustment device

1 - Horizontal angle adjustment device; 2 - Square tube outside the vertical beam; 3 - Vertical telescopic adjustment device; 4 - Bottom hydraulic cylinder support beam; 5 - Vertical angle adjustment device; 6 - Horizontal telescopic beam; 7 - Base beam; 8 - Horizontal telescopic adjustment device;

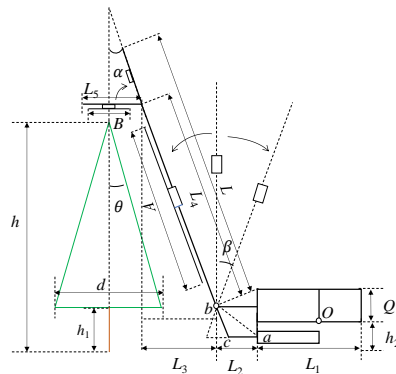


Fig. 5 - Schematic diagram of the pruning mechanism

According to the standard, a dwarf rootstock densely planted with tall spindle apple trees, with a height 'h' of 4 meters, the height 'h1' of the tree trunk is 0.7 meters, and the tree canopy diameter, denoted as 'd', is 1.2 meters. The geometric relationship between pruning machinery and fruit trees, as shown in Fig 5, requires pruning machinery to form a certain angle with the fruit tree during operation, which was approximately equal to the angle between the crown and the main trunk, then it was:

$$\tan \alpha \approx \tan \theta = \frac{d/2}{h - h_1} \tag{1}$$

α - the angle between the main trunk of the fruit tree and the pruning machinery, [°];

θ - the angle between the main trunk and the crown of the fruit tree, [°];

The angle of inclination of the vertical pruning device was found to be $\alpha = 17^\circ$. The height of the pruning machine should be greater than the tree height, therefore:

$$(L + l_{4\max}) \cos \alpha + h_2 + Q/2 > h \tag{2}$$

h_2 - the distance between the installation position of the trimming device and the ground, [m];

$l_{4\max}$ - maximum extension of vertical telescopic hydraulic cylinder, [m];

Q - width of horizontal telescopic adjustment device, [m];

In formula (2), $h_2 = 0.4$ m, $l_{4\max} = 0.5$ m, the total length L needs to be greater than 3.1 m, considering the actual working condition, the final design was $L = 3.4$ m, horizontal section length $L_5 = 1.1$ m, effective sawing length $B = 1$ m; length of vertical section $L_4 = 2.3$ m, effective sawing length $A = 2.2$ m; inclination angle 22° , camber angle 17° . When the length adjustment hydraulic cylinder was telescoped to the design maximum $l_{1\max} = 0.5$ m, $l_{4\max} = 0.5$ m; at this time the camber angle was 17° , then $\angle acb = 107^\circ$, the length of ab , bc can be measured directly, the length of L_2 can be based on the cosine theorem (3) to find, $L_2 = 139$ mm.

$$\cos \angle acb = \frac{L_2^2 + L_{bc}^2 - L_{ab}^2}{2L_2 \cdot L_{bc}} \tag{3}$$

When the state of the adjusting device was: the horizontal trimming device was parallel to the ground, and the vertical angle adjusting device was at the maximum camber angle, the mathematical model was constructed based on the designed data with the point O as the coordinate origin, as shown in formula (4).

$$\begin{cases} X_o = l_{1\max} + L_2 + L_3 + L_5 \\ Y_o = (L_4 + l_{4\max}) \cos \alpha + Q/2 \end{cases} \tag{4}$$

$$L_3 = (L_4 + l_{4\max}) \sin \alpha \tag{5}$$

$l_{1\max}$ - maximum extension of horizontal telescopic hydraulic cylinder, [m];

L_2 - vertical angle adjustment of hydraulic cylinder extension, [m];

The trajectory in the horizontal direction $X_o = 2404$ mm, which was also smaller than the planted row spacing under the consideration of the tractor width, so the adjustment amount of the pruning device was sufficient; the trajectory in the vertical direction $Y_o = 2932$ mm, which was smaller than the tree height of 4 m.

When the state of the adjusting device was: the horizontal trimming device and the vertical angle adjusting device were at the same time at the maximum camber angle of 17° , the mathematical model was constructed with the point O as the coordinate origin according to the designed data:

$$\begin{cases} X_o = l_{1\max} + L_2 + (L_4 + L_5 + l_{4\max}) \sin \alpha \\ Y_o = (L_4 + L_5 + l_{4\max}) \cos \alpha + Q/2 \end{cases} \tag{6}$$

The horizontal trajectory $X_o = 1779$ mm, can work normally; the vertical trajectory $Y_o = 3985$ mm, slightly less than the tree height of 4m, can complete the pruning of the top of the apple tree, so the design meets the requirements.

Circular saw blade analysis

In the trimming operation, the circular saw blade had a feed rate along the X -axis and rotated around the Z -axis. The sawing force was mainly composed of tangential force F_t , radial force F_n and axial force F_a , as shown in Fig. 6. Radial force was the main force of the trimming operation, acting in the direction of the radius of the circular saw blade; tangential force acted in the direction perpendicular to the radial force; axial force acted in the direction perpendicular to the surface of the saw blade, causing lateral vibration of the saw blade (Wang Z et al., 2017).

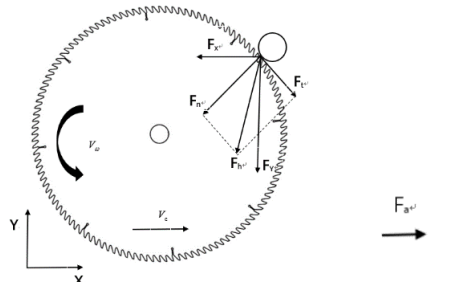


Fig. 6 - Force diagram of circular saw blade

Due to the woody properties of apple branches, which were anisotropic materials, and the influence of many external factors during sawing, it was a complex nonlinear process, so, in order to simplify the calculation of sawing forces, dynamics need to be constructed for the whole system for analysis. The constructed kinetic model can have multiple variables and applies to nonlinear problems, which could be verified by kinetic simulation later (Meng Y. et al, 2020). To facilitate the calculation, decompose the combined tangential and radial forces in *X* and *Y* directions respectively and perform force analysis, as shown in Fig. 6.

In the *X* direction:

$$F_x = F_t \cos \beta - F_n \sin \beta - c \frac{dx}{dt} - kx \tag{7}$$

In the *Y* direction:

$$F_y = -F_n \cos \beta - F_t \sin \beta - c \frac{dy}{dt} - ky \tag{8}$$

The force in the *Z* direction was equivalent to the axial force:

$$F_z = F_a \tag{9}$$

β - angle of radial force to *Y*-axis, [°];

c - damping of apple tree branches, [Nm/s];

k - stiffness of apple tree branches, [N/m];

x, y - displacement of circular saw blade in *X*-direction and *Y*-direction, [m];

According to the spatial mechanic's relationship the sawing force *F* was:

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{10}$$

According to the research, the main factor affecting the sawing force is the feed per tooth, calculated by the formula (11) (Zhang B et al., 2022), and the feed per tooth was directly proportional to the feed speed and inversely proportional to the speed and number of teeth.

$$V_z = \frac{1000 \cdot V_c}{n \cdot z} \tag{11}$$

V_z - feeds per tooth, [mm];

V_c - linear feed speed, [m/min];

n - circular saw blade speed, [rpm];

z - number of teeth of circular saw blade.

The branch sawing process in the orchard was an unsupported cutting method, and studies had shown that the working line speed for unsupported cutting must not be less than 30 m/s (Liu J et al., 2021), bringing in the data, the minimum speed of a circular saw blade with a diameter of 400 mm was found to be 1433 rpm.

$$n = \frac{60V_a}{\pi D} \tag{12}$$

V_a - linear speed of saw blade, [m/s]; *D* - circular saw blade outer diameter, [m];

A three-dimensional model of the circular saw blade was created using the dimensions given in Table 1, and then modal analysis was performed on the established model.

Table 1

Circular saw blade size parameters						
Outer diameter / (mm)	Inner diameter / (mm)	Thickness / (mm)	Number of teeth	Front corner / °	Rear corner / °	Materials
400	30	3	120	15	15	65Mn

According to Table 2 (Wu Q.B. et al., 2020), the material parameters of the circular saw blade were assigned and meshing was performed. The mesh cell size of the circular saw blade mesh was 2.0 mm.

Table 2

Circular saw blade material parameters				
Poisson's ratio	Modulus of elasticity / (MPa)	Density / (kg/m ³)	Yield limit / (MPa)	Shear modulus / (MPa)
0.3	2.06e ⁵	7850	440	80000

Sixth-order modal analysis of the circular saw blade was performed by Workbench, and the inherent frequency and maximum displacement of the circular saw blade was obtained, as shown in Table 3, as well as the first six-order modal vibration diagram, as shown in Fig 7.

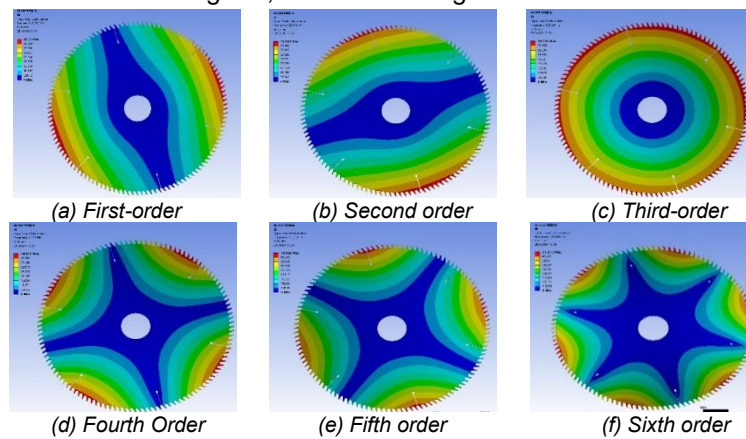


Fig. 7 - Sixth-order modal diagram of circular saw blade

Table 3

The first six natural frequencies and the maximum displacement						
Mode order	1	2	3	4	5	6
Frequency / (Hz)	82.99	83.12	92.37	113.50	113.53	222.06
Displacement / (mm)	45.73	45.49	32.80	48.02	49.09	51.38

According to the vibration diagram of the first six orders of modes, it was obtained that the circular saw blade mainly oscillates or deforms reciprocally along the X-axis, Y-axis, Z-axis and the blade teeth around the circular saw blade. From Table 3, the first-order intrinsic frequency of the circular saw blade was 82.99 Hz, and according to the speed and frequency equation (13) (An R., 2019), the critical speed of the circular saw blade was 4980 rpm, and the stable speed of the circular saw blade was better than 15% of its critical speed, so the critical speed was 4233 rpm.

$$n = 60 \cdot f \tag{13}$$

f – frequency, [Hz].

Finite element modeling and simulation analysis of sawing process

Circular saw blade sawing of branches belongs to the contact nonlinear type material impact dynamics problem (Wang X.C. et al., 2015; Sun et al., 2022), and the process is relatively complex. In order to facilitate the calculation, it is necessary to simplify the whole sawing model while ensuring the simulation results are as close to the real situation as possible. Then, the branch was defined as a Solid unit and its material was set to *MAT_ORTHOTROPIC_ELASTIC. Since the apple branch will break when it was sawed, for this reason, it was necessary to add the keyword *MAT_ADD_EROSION. material parameters, as in Table 4 (Jiang L Q, 2013).

Table 4

Branch material parameters	
Parameter Name	Parameter Value
Density / (kg/m ³)	550
Paramagnetic modulus of elasticity / (MPa)	29.8
Horizontal radial modulus of elasticity / (MPa)	439.8
Horizontal chordal modulus of elasticity / (MPa)	15.5
Parallel grain shear modulus of elasticity / (MPa)	26.7
Horizontal radial shear modulus of elasticity / (MPa)	18.3
Horizontal chordal shear modulus of elasticity / (MPa)	1.8
Parallel Poisson's ratio / (MPa)	0.46
Horizontal radial Poisson's ratio / (MPa)	0.031
Horizontal chordal Poisson's ratio / (MPa)	0.015

The circular saw blade was defined as a Solid unit, set the material as *MAT_RIGID, material parameters as shown in Table 2. Set the contact to *CONTACT_ERODING_SURFACE_TO_SURFACE, applied a fixed constraint to the bottom of the branch, gave the circular saw blade a feed speed of 3 km/h along the X-axis and a rotation speed of 3000 rpm around the Y-axis, and constrained the tool Y and Z direction movement and rotation around the X and Y axis.

RESULTS AND ANALYSIS

Single factor test

The branch diameter was selected to be 20 mm at a feed speed of 3 km/h. The rotational speeds of 500 rpm, 1000 rpm, 2000 rpm, 3000 rpm and 4000 rpm were selected for the test. The obtained trend of sawing force with speed was shown in Fig 8. At low speed, the sawing force was very large and difficult to say, with the increase of speed, the sawing force decreased rapidly and tended to be stable gradually, when the speed reached 3000 rpm, the sawing force started to increase slowly. According to the formula (11), the smaller the rotational speed, the larger the feed per tooth, and the more cutting volume would increase, resulting in an increase in sawing force. When the rotational speed exceeds the allowed range, the saw blade will vibrate significantly, so the rotational speed should be selected from 2000 to 3000 rpm.

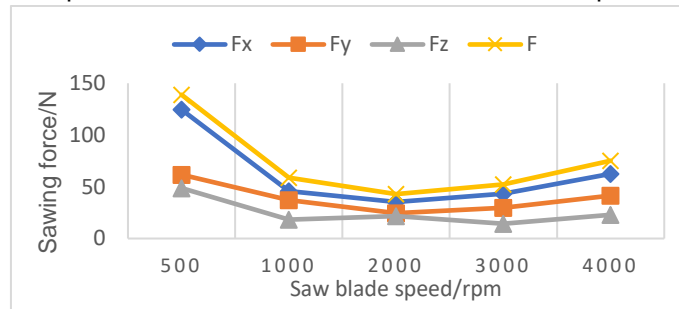


Fig. 8 - Relationship between saw blade speed and sawing force

Selecting the diameter as 20 mm and saw blade speed as 3000 rpm, the simulation was carried out for the feed speed of 1~5 km/h respectively, and the data obtained is shown in Fig 9. From equation (11), it can be seen that the increase in feed speed would lead to an increase in sawing difficulty, so the sawing force had been increasing. As can be seen from Fig 11, the feed speed increased faster after 3 km/h. Taking into account the efficiency and sawing difficulty and other factors, the feed speed of 3~5 km/h was selected.

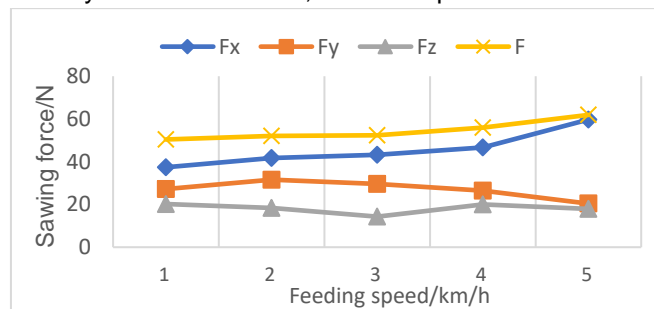


Fig. 9 - Relationship between feed rate and sawing force

The speed of 3000 rpm and feed rate of 3 km/h were chosen to simulate the branch diameter of 10~40 mm respectively, and the test results are shown in Fig 10. The circular saw blade was easier to cut branches below 20 mm in diameter, when the diameter exceeded 20 mm, the growth rate of the sawing force required for cutting was greatly accelerated, especially the axial force, which may lead to the deformation of the circular saw blade when cutting large diameter branches.

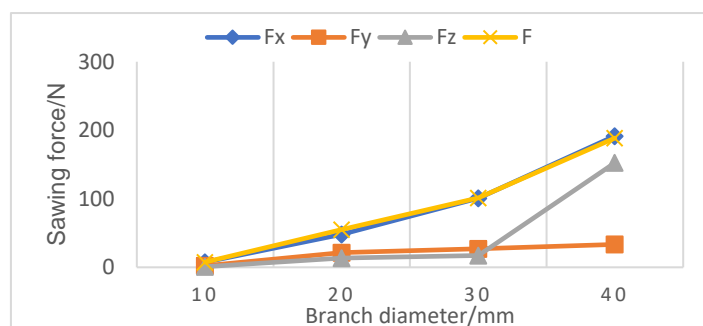


Fig. 10 - Relationship between branch diameter and sawing force

Orthogonal test

A three-factor, three-level quadratic orthogonal test was designed according to the Box-Behnken principle to analyse the effect on sawing force when multiple factors acted simultaneously on the basis of a single factor and to seek the optimal parameter fit (Kang F et al.,2020), with the parameters shown in Table 5.

Table 5

Orthogonal test element level table

Branch diameter (A) /(mm)	Saw blade speed (B) /(rpm)	Feeding speed (C) /(km/h)
10	2600	3
20	2800	4
30	3000	5

The quadratic polynomial regression was fitted to the test data using Design-Expert 8.0.6, and the resulting regression equation (14), and the regression equation ANOVA was performed on the results of the central combination test, and the results were shown in Table 6.

$$F = 48.76 + 44.49A + 2.57B + 5.29C - 1.95AB + 2.18AC - 1.95BC + 4.53A^2 + 3.16B^2 + 1.08C^2 \quad (14)$$

Table 6

Regression equation analysis of variance

Source	Squares	DF	MS	F value	P value
Models	16304.00	9	1811.56	211.63	< 0.0001
A	15833.10	1	15833.10	1849.68	< 0.0001
B	53.05	1	53.05	6.20	0.0416
C	223.66	1	223.66	26.13	0.0014
AB	15.21	1	15.21	1.78	0.2243
AC	18.92	1	18.92	2.21	0.1807
BC	15.21	1	15.21	1.78	0.2243
A²	86.50	1	86.50	10.11	0.0155
B²	41.98	1	41.98	4.90	0.0624
C²	4.93	1	4.93	0.58	0.4725
Residual	59.92	7	8.56		
Lack of Fit	45.27	3	15.09	4.12	0.1025
Pure Error	14.65	4	3.66		
Cor Total	16363.92	16			

Note: $P < 0.01$ (extremely significant, **), $P < 0.5$ (significant, *)

As shown in Fig.11 (a), the feed speed and branch diameter are positively correlated with the sawing force when the branch diameter is constant, and the correlation between the two is close; the effect of the saw blade speed on the sawing force is more significant than the feed speed; when the feed speed is certain, the sawing force increases with the increase of the saw blade speed. As shown in Fig.11 (b), the correlation between branch diameter and sawing force is extremely significant at a certain feed speed, while the correlation between saw blade speed and sawing force is negative and increases with the increase of feed speed. The influence of branch diameter on the sawing force is much more significant than the saw blade speed, when the saw blade speed is certain, the sawing force increases with the increase of branch diameter.

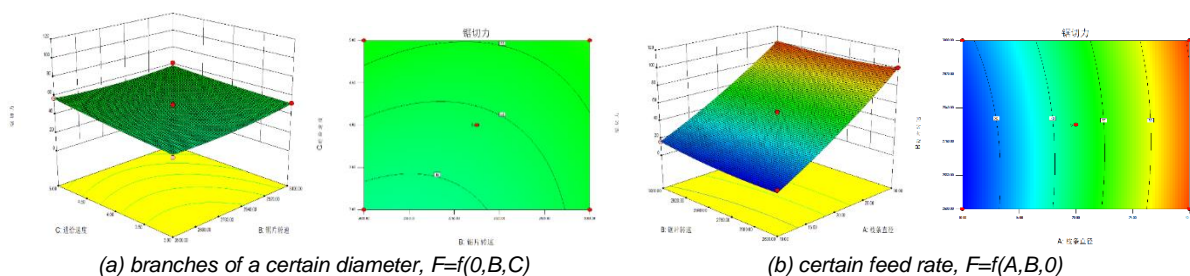


Fig. 11 - Response surfaces of sawing forces under different conditions

The optimal solution derived from the orthogonal test was 2800 rpm for the saw blade speed and 4 km/h for the feed speed at a branch diameter of 20 mm, but the actual working conditions need to be considered, so field performance tests need to be conducted for further verification.

Prototyping and field trials

To verify the functionality and reliability of the apple pruning machinery and the degree of fit of the designed sawing parameters, the overall prototype was tried and field trials were conducted as shown in Fig.12. The test was conducted in March 2022 at the test base of Gaomi Yifeng Machinery Co.

The test conditions included: Dongfanghong X700 tractor with a calibrated power of 51.5 kW; the orchard was planted with standardized dwarf anvil and dense planting; the pruning machine prototype with circular saw blade speed selected at 2800 rpm.



Fig. 12 - Prototype trial production and field test

During the test, the pruning machinery was sensitive to action, and the automatic obstacle avoidance function was good. The position adjustment process was smooth and fluid. The apple pruning machine was mainly used for pruning dwarf dense orchards with short anvils, so the main test was the qualified rate of pruning. 9 areas were selected as test points, each area includes about 20 branches, and the qualified rate was tested under different feeding speeds, the test data was shown in Table 7.

Table 7

Experimental data statistics									
Test site	1	2	3	4	5	6	7	8	9
Feeding speed/ (km/h)	3	3	3	4	4	4	5	5	5
Passing Rate/ (%)	89.5	86.8	90.2	92.1	97.5	88.9	88.3	91.2	87.1

The main criteria for passing rate are: branches missed cut, not cut and extremely rough cut surface covered with burrs are considered as failing, while other cases are considered as passing (Chang J X., 2019). The cut quality is mainly influenced by the saw blade speed, feed rate and branch diameter. At the saw blade speed of 2800 rpm, most of the branches could reach the passing standard, and the average passing rate at the feed speed of 4 km/h was 92.8% higher than 88.8% at 3 km/h and 88.9% at 5 km/h, and the overall average passing rate reached 90.2%. When the saw blade speed is reduced, the quality of the section decreases, the burr increases and the passing rate decreases. After the test, the best sawing parameters were obtained to match the saw blade speed of 2800 rpm and the feed speed of 4 km/h.

CONCLUSIONS

(1) This pruning machine is suspended from the front of the tractor and uses a hydraulic motor to drive a circular saw blade for pruning operations. The dimensions of the pruning device are determined according to the planting requirements of dense apple orchards with dwarf anvils: horizontal section length $L_5 = 1.1$ m, vertical section length $L_4 = 2.3$ m, inclination angle 22° and inclination angle 17° .

(2) Sawing process analysis and modal analysis were carried out for the saw blade, and the limit speed of the circular saw blade was determined. Through finite element simulation analysis, a reasonable range of circular saw blade speed, branch diameter and feed speed was derived, and a three-factor, three-level quadratic orthogonal test was designed according to the Box-Behnken principle. The experiment showed that when the diameter of the cut branch was 20 mm, the best cutting effect was achieved with a saw blade speed of 2800 rpm and a tractor feed speed of 4 km/h.

(3) The prototype and field test was carried out, and the test results showed that the low saw blade speed would lead to an increase in the cut burr, and the fast tractor feed speed would lead to incomplete cutting of the branch and tearing of the epidermis of the branch. The test results showed that when the saw blade speed was 2800 rpm and the tractor was at 4 km/h, the sawing effect was the best and the average passing rate reached 92.8%, which was consistent with the simulation results and the cutting quality met the pruning requirements of the new orchard.

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