Design of multi-section luffing apple pruning equipment and cutting test of the key components

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Abstract: In order to reduce the labor intensity and improve the efficiency of pruning, this study designed a multi-section luffing apple pruning equipment suitable for apple orchards in hilly and mountainous areas of China. In the essay, the structure and working principle of the equipment are expounded, the cutter was analyzed, and the parameters were determined. Using the self-made test bench to simulate the field experiment, this study selected the ratio of cutting speed to feeding speed and feeding speed as the influencing factors and took the cut-off rate, cutting efficiency and cutting power as the objectives to carry out single factor experiment and quadratic regression orthogonal experiment. The test results show that the cutting power increases with the increase of ratio of cutting speed to feeding speed, and the cut-off rate and cutting efficiency first increase and then decrease. As the feeding speed increases, the cutting efficiency and power increase, and the cut-off rate decreases. When the cut-off rate was greater than 80%, the optimal combination of operating parameters was the feeding speed of 0.55 m/s and ratio of cutting speed to feeding speed of 1.29. Under this combination, the cut-off rate was 84.9%, the cutting efficiency was 13.1, and the cutting power was 175.7 W. The error between the predicted target value of the model and the average measured target value was less than 7%, so the test results are reliable. According to the obtained optimal operating parameters, the actual cutting experiment of the pruning equipment in the field was carried out, and the cutting rate was 96.3%, which meet the design requirements. This study can also meet the needs of mechanized pruning of fruit trees with different crown shapes, improve the applicability of pruning equipment, and provide support for the development of mechanized pruning equipment in China.

Keywords: apple, pruning equipment, cutting test, optimal parameters, regression analysis

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1 Introduction

As an important part of the fruit industry, the total output of apples in the world in 2020 was 86.4427 Mt, of which China's output was 40.5 Mt, accounting for 46.9% of the total output of apples in the world, and ranking first in the world[1]. As orchards are mostly distributed in hilly and mountainous areas, the production efficiency and mechanization level of orchards are extremely low due to the influence of geographical environment and economic development level[2]. At present, the pruning is still mainly manual pruning, coupled with manual pruning shears, using stools or ladders for operation, which has low efficiency, high strength and high risk[3]. As the population ages and rural labor migrates, the average labor cost of pruning has reached 52%, and the development of apple industry has been restricted[4,5]. With the popularization of the apple dwarf stock and dense planting cultivation mode[6], the construction of standardized orchards has accelerated. Simply relying on manual pruning can no longer meet production needs[7], and the demand for mechanized pruning equipment is increasingly urgent.

The foreign research on fruit tree pruning equipment started earlier, such as the reciprocating, rotary blade and circular saw mechanical pruning equipment designed by Edwards company of Germany, FA-Ma company of Italy[8], Fred spagnolo of Australia[9,10], Spencer[11], which were suitable for standardized apple and grape tree pruning operations and realized one-sided or two-sided pruning, with good operation effect and high reliability. In China, there are several researchers have studied the structure and parameters of fruit tree pruning equipment. Some of them focused on the reciprocating pruning equipment and achieved certain results. For example, the 3PJ-1 gantry grape pruning equipment has been upgraded for four generations to reduce power consumption and improve working efficiency, which the pruning rate was 95.9%[12]; Through theoretical analysis and simulation to determine the parameters of key components, Zhang et al.[13] developed a single motor reciprocating grape pruning equipment and achieved the stalk shear net rate of 90.66% and the pruning rate of 4.71% in field test; The reciprocating grape pruning equipment designed by Long has carried out the cutting test of the test bench, and obtained the test parameters of the best pruning effect[14]. In addition, there are also some studies focusing on the rotary blade pruning equipment. For instance, the PJS-1 grape pruning equipment[15] could prune the side and top of two rows of grapevines at one time through hydraulic drive, with the good pruning effect; Han et al.[16] designed the summer wine grape pruning equipment, determined the optimal combination of operation parameters by using the Box-Benhnken

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center combination test, and the best cutting rate was 96%. In addition, the circular saw pruning equipment includes the citrus trimmer with bilateral and neat trim[17] and the profiling pruning equipment[18], the cutting rate was about 90%, which met the pruning requirement.

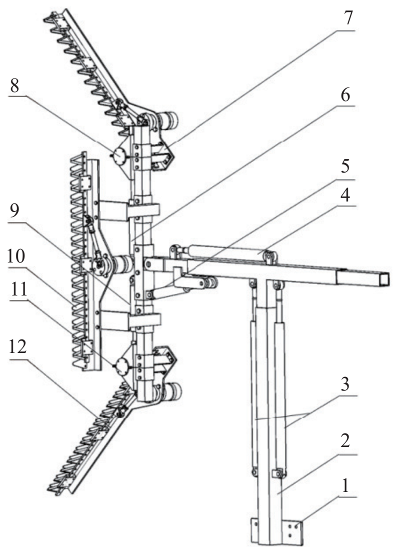
Cutting parameters and operating parameters of key cutting components are the basis for research on mechanical pruning. Crop stalks are composite material, with different physical characteristics and different cutting power consumption during cutting[19]. According to the three cutting types, a large number of studies have been carried out on the cutting performance of crop stalks. Reciprocating cutting can be divided into quasi-static shearing (cutting velocities are less than 30 mm/s) and cutting with a counter-edge (at velocities greater than 0.5 m/s)[20]. The quasi-static shearing was tested with an electronic universal testing machine (UTM). Liu et al.[21] studied the relationship between the blade angle, sliding-cutting angle, cutting speed and the cutting force, cutting power consumption of peony stalks, and obtained the blade parameters under the lowest cutting force and cutting power consumption: 25° blade angle and 20° sliding-cutting angle for peony stems in anthesis, 25° blade angle and 10° sliding-cutting angle for stems in fructescence. Cutting force and cutting power of hemp stem increased with moisture content and density[22]. For corn stalk, Igathinathane et al.[23] studied the effect of cutting direction, stalk size and stalk position on cutting force and cutting power consumption, and tested peak torque, peak stress and cutting energy by a digital torque wrench (DTW) and UTM[24]. Tian et al.[25] designed the bionic cutting blade according to the structure of longicorn mouthparts palate, and found that the cutting force and cutting energy consumption of the bionic blade were reduced by 12.89% and 10.73% respectively compared with ordinary blade. In a counter-edge cutting experiment, the response surface methodology (RSM) was used to explore the relationship between cutting force and cutting power consumption of maize stalk by taking approach angle, feed angle and cutting velocity as experimental factors. The cutting force and cutting power consumption were reduced by 2.3 times and 4 times respectively under the optimal parameters[26]. The cutting height and moisture content of canola stalk had significant effects on cutting power consumption, and the highest cutting energy consumption was 1.1 kJ and the lowest was 0.76 kJ[27]. Gao et al.[28] obtained the optimal combination of parameters under the supported cutting of Caragana korshinskii (C.k.) as cutting speed of 3.36 m/s, wedge angle of 20° and slip cutting angle of 20°. In related cutting tests for rotary cutting, Johnson et al.[29] and Mathanker et al.[30] used the same test bench to study the cutting energy of miscanthus and energycane stems under different oblique angles, cutting speeds and stem diameters. Gao et al.[28] and Allameh et al.[31] toke cutting speed, wedge angle and slip cutting angle as experimental factors to obtain the minimum unsupported cutting power consumption. Hou et al.[32] obtained the optimal blade parameters (blade angle 14.06°, slip angle 19.93° and cutter head inclination angle 10.54°) through finite element model and response surface analysis. In the kenaf stem cutting experiment, Ghahraei et al.[33] pointed out that the cutting speed increased when the cutting torque decreased, and the optimal parameters were knife edge angle 25°, knife shear angle 40°, knife approach angle 40° and knife rake angle 40°.

To sum up, pruning equipments are still in the design and development stage in China, which are mostly applied to pruning grape vines with a single object. Foreign pruning equipment can prune the side and top of canopy, but they cannot prune fruit trees with complex shapes. Moreover, it is difficult to popularize and apply widely in China due to its high price, high maintenance cost and difficult adaptation of tractors. Therefore, this study designed a multi-section luffing pruning equipment, which can prune high spindle apple trees by adjusting the relative positions of the upper, mid and lower cutter, and also adapt to the pruning of various tree shapes such as spherical and trapezoidal. In addition, the operating parameters of the machine have a greater impact on the operating effect[34,35], the above cutting test objects were all single stem, so it is impossible to explore the operating parameters of the pruning equipment. The optimal parameters of reciprocating cutting have been determined in the previous research[36]. In this study, the self-made reciprocating key cutting component test bench will be used to simulate the actual cutting conditions in the field. Selecting the ratio of cutting speed to feeding speed and branch feeding speed as the test factors, and the cut-off rate, cutting efficiency and cutting power as the target value for the cutting test, this study is going to analyze the influence of various factors on the target value, and seek the optimal combination of operation parameters, and finally verify the reliability of the pruning equipment through field experiments. This study effectively improves the pruning efficiency and reduces the labor cost, which is of great significance for the development of the fruit industry.

2 Structure and working principle of pruning equipment

2.1 Structure of pruning equipment

The multi-section luffing pruning equipment was composed of front suspension device, frame, hydraulic cylinder, upper cutter, upper cutter connecting device, mid cutter, lower cutter connecting device, lower cutter and other mechanisms. Its structure is shown in Figure 1.



1. Front suspension 2. Frame 3. Lifting motion hydraulic cylinder 4. Lateral motion hydraulic cylinder 5. Pitching hydraulic cylinder 6. Upper cutter luffing hydraulic cylinder 7. Upper cutter 8. Upper cutter connecting device 9. Lower cutter luffing hydraulic cylinder 10. Mid cutter 11. Lower cutter connecting device 12. Lower cutter

Figure 1 Structure diagram of pruning equipment

2.2 Working principle

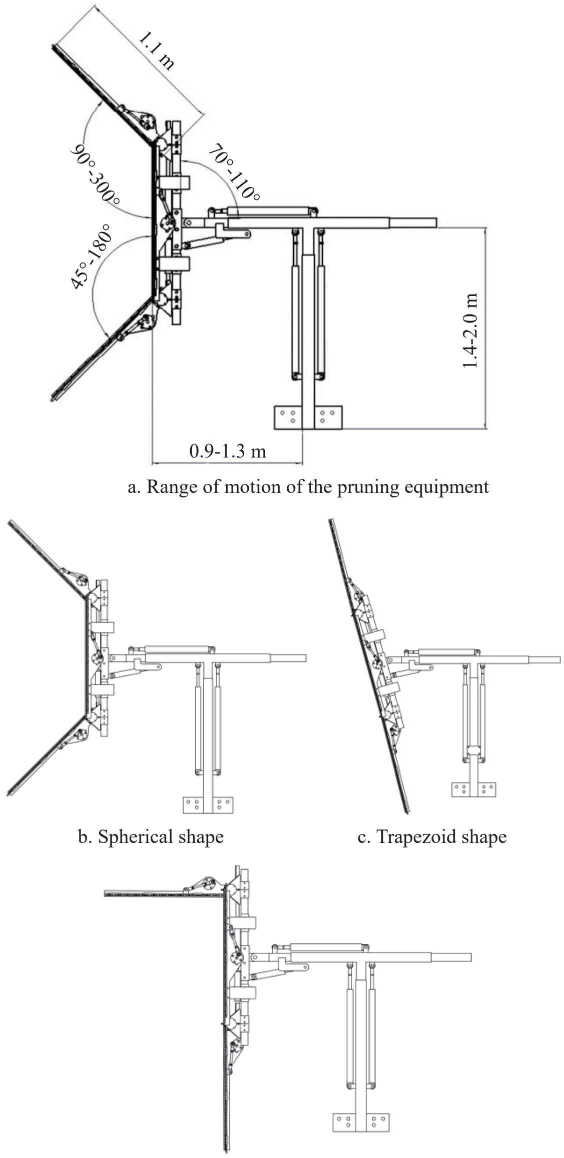
When the pruning equipment was working, the tractor PTO (power take off) and the gear pump provide power for the hydraulic cylinder and the hydraulic motor to realize the luffing motion and the cutting motion of the cutter. The pruning equipment was hung in front of the tractor, and the fuel tank was mounted at the back of the tractor, which is convenient for the driver to observe the operation condition and ensure the stability of the tractor. The hydraulic cylinder and the hydraulic motor were controlled by the solenoid valve switch, and the pruning equipment can be controlled in the tractor cab through the control device.

After the high spindle apple tree is formed, the tree height is 3.5-4.0 m, the average crown width is 2 m, the plant spacing is 0.9-1.2 m, and the row spacing is 3.3-3.9 m[37]. On this basis, the structure and size of the pruning equipment were reasonably designed, the Lovol M604-B tractor was selected, and the hydraulic system was calculated and selected according to the tractor parameters. The relevant parameters are listed in Table 1.

Table 1 Parameters of pruning equipment

Parameters	Unit	Values
PTO rotating speed	$r\cdot min^{-1}$	0-760
Hydraulic motor displacement	$mL\cdot r^{-1}$	50
Average cutting speed	$m\cdot s^{-1}$	0-1.4
Average forward speed	$km\cdot h^{-1}$	0-30

There were six hydraulic cylinders connected in the hydraulic system to drive the lifting, lateral, pitching, and luffing of the upper cutter and lower cutter of the pruning equipment. The range of motion is shown in Figure 2. It can meet the needs of mechanized shaping and pruning of different crown-shaped fruit trees. The luffing of the upper and lower cutters was realized by the gear-rack mechanism driven by the hydraulic cylinder, and cutters can be folded when it is not working to reduce the space. The other three hydraulic motors drove the crank linkage mechanism to realize the cutting motion of the upper, mid and lower cutter, and change the cutting speed of the cutter by controlling the PTO rotating speed. Before pruning, the cutter was adjusted to a proper position to be driven and the tractor is driven into the orchard for cutting.

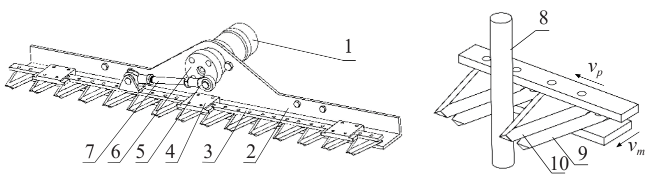


a. Range of motion of the pruning equipment

b. Spherical shape c. Trapezoid shape

d. Wall shape

Figure 2 Range of motion and pruning shape of the pruning equipment



1. Hydraulic motor 2. Fixed blade holder 3. Moving blade bar 4. Blade clips 5. Fisheye ball bearing 6. Crank disc 7. Connecting rod 8. Branch 9. Fixed blade 10. Moving blade

Figure 3 Structure diagram of cutter

3 Design of key components

3.1 Cutter

Among the three cutting types, rotary blade and circular saw have high cutting efficiency and high cutting power consumption, it is suitable for pruning soft branches such as grapes; reciprocating cutter has good cutting effect, low power consumption and good versatility, it is suitable for pruning dwarfed and densely planted fruit trees (apples, citrus, etc.)[38]. Considering the complexity of the terrain of orchards in hilly and mountainous areas, and meeting the design requirements of simple and compact equipment structure, the equipment adopted the reciprocating single moving blade cutting mode. As shown in Figure 3, moving blades were mounted on the moving blade bar, and fixed blades were fixed on the fixed blade holder. The cutter powered by the hydraulic motor, moving blades were driven to reciprocate in the blade clips through the crank linkage mechanism, and complete the cutting with fixed blades. The branches were fed continuously with the advance of the cutter, where v_p is the average cutting speed of the blade, and v_m is the forward speed of the cutter.

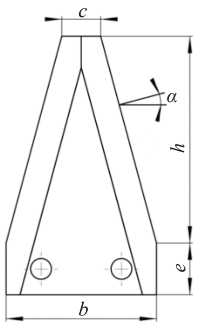
3.2 Analysis of cutting principle

3.2.1 Blade parameters

Blade parameters are the main factors affecting the cutting force. The cutting mechanical characteristics of apple branches have been explored before[36], and the blade size is determined as shown in Figure 4. The results demonstrate that the peak cutting force increases linearly with the branch diameter, but decreases when the average cutting speed and sliding cutting angle are increasing, and decreases first and then increases with the increase of the cutting gap.

3.2.2 Operating parameters

During the cutting operation, the cutter motion consists of two parts: forward motion and reciprocating cutting motion. The forward motion is constant speed. The reciprocating cutting motion is driven by an offset crank linkage mechanism and the relationship between speed and time is sinusoidal, the average cutting speed v_p of the cutter is taken as the evaluation index:



Note: The edge height h is 80 mm, the sliding cutting angle α is 15°, the holder length e is 20 mm, the blade width b is 58 mm, the blade front axle width c is 15 mm, the material is 65Mn.

Figure 4 Parameters of cutting blade

$$v_p = \frac{2Sr}{60} = \frac{Sr}{30} \tag{1}$$

where, v_p is the average cutting speed, m/s; S is the cutter stroke, m; r is the crank rotating speed, r/min.

In order to analyze the influence of the two motions on the cutting effect, the cutter feed pitch (the forward distance of the cutter within one stroke) and the ratio of cutting speed to forward speed are calculated, as shown in Equations (2) and (3).

$$H = v_m \frac{\pi}{\omega} = \frac{30 v_m}{r} \tag{2}$$

$$k_1 = \frac{v_p}{v_m} = \frac{Sr/30}{Hr/30} = \frac{S}{H} \tag{3}$$

where, H is the cutter feed pitch, m; v_m is the forward speed,m/s; ω is the crank angular velocity, rad; k_1 is the ratio of cutting speed to forward speed.

The cutting track of the cutter is shown in Figure 5. The cutting area can be divided into three different situations: Ⅰ is the repeated cutting area. After the branches are cut in this area, the cutting stubble touches again through the return movement of the moving blade, which may lead to secondary cutting and subsequent reduction of stubble quality. The larger the area, the more useless work will be consumed. Ⅱ is the primary cutting area, which is the normal operation area. Ⅲ is the missed cutting area where the branches have not been cut and may be pushed down during advancement, resulting in partial breaking and missed cutting. Therefore, the area Ⅰ and Ⅲ should be reduced to improve the cutting efficiency during the operation. With the increase of v_m, the area Ⅰ decreases, the area Ⅲ increases, and the quality of stubble decreases; as the v_p increases, the area Ⅰ increases, the area Ⅲ decreases, and the vibration of equipment increases. The influence of operation parameters on cutting effect is relatively complex, so this study is going to explore the relationship between operation parameters and cutting effect through experiments in part 4.

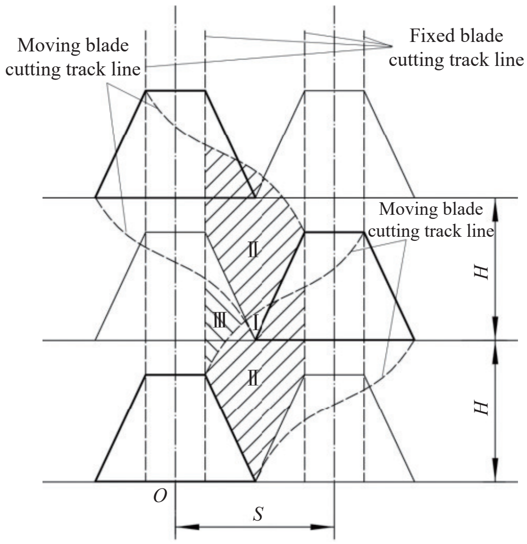


Figure 5 Cutting trace

4 Cutting test of key components

4.1 Test material

The apple branches were taken from an apple orchard in Qinhuangdao City, Hebei Province, China. The variety is “Red Fuji”. The branch picking time was March 2021 when the tree age is 6 years. The branches were sealed and stored indoors. The selected branches were free of diseases, insect pests and obvious defects. The branches were basically straight, with a diameter ranging from 8 to 10 mm and a length of 250 mm. The moisture content was 18.5% to 23.4%, and the density was 597.7 kg/m^3.

4.2 Cutting test bench

The self-designed and manufactured cutting test bench was used for the test, as shown in Figure 6. The cutting test bench consists of three parts: cutting system, branch feeding system and measurement and control system.

1) Cutting system

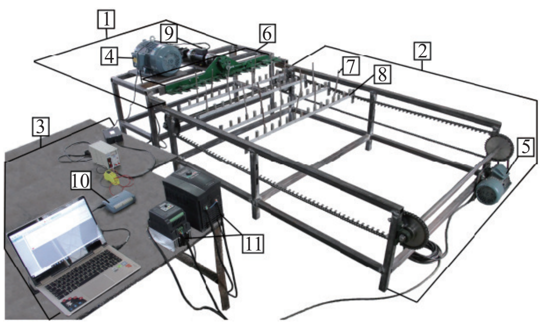
The cutting system was composed of cutting frame, AC motor, bearing block, coupling, cutter, etc. The crank train was driven by the motor through V-belt and coupling to drive the cutter to realize reciprocating cutting movement.

2) Branch feeding system

The branch feeding system consisted of feeding frame, AC motor, chain, sprocket, branch clamping device, etc. The branches were fixed on the clamping device, which was connected with the chain. The motor drove the sprocket to rotate. The branches were fed through the chain drive to replace the forward motion of the pruning equipment.

3) Measurement and control system

The measurement and control system consisted of a notebook computer, dynamic torque sensor and its transmitter, variable-frequency drive, data acquisition board NI-MCC1608G-USB, and 24 V power supply. Two frequency conversion drives controlled the speeds of the AC motors to achieve different cutting speeds and feeding speeds. The dynamic torque sensor was connected in series between the two rigid couplings to measure cutting force and crank speed.



1. Cutting system 2. Branch feeding system 3. Measurement and control system 4. Cutting system motor 5. Feeding system motor 6. Cutter 7. Apple branches 8. Branch clamping device 9. Torque sensor 10. Data acquisition board NI-MCC1608G-USB 11. Variable-frequency drive

Figure 6 Cutting test bench

The technical parameters of the cutting test bench are listed in Table 2.

Table 2 Technical parameters of cutting test bench

Parameters	Unit	Values
Average cutting speed	$m\cdot s^{-1}$	0-1.8
Average feeding speed	$m\cdot s^{-1}$	0-1.2
Power of cutting motor	kW	4
Power of feeding motor	kW	2.2
Cutter stroke	mm	76
Cutting width	mm	1100
Torque sensor range	N·m	50
Acquisition frequency of daq	Hz	500
Data acquisition channel		1

4.3 Design of tests

4.3.1 Test method

The continuous cutting test of multiple branches with reciprocating single movable blade was carried out on the cutting test bench. The apple branches were placed in the branch clamping device, and then start the cutting system motor. After the average cutting speed was stable, the feeding system motor was turned on. There was a certain forward distance before the branches were cut to ensure that the branches were fed at a uniform speed. Finally, the measurement system was used to record and store the torque during cutting. In each group, 20 branches were cut and each cutting repeated for 3 times. The branches were randomly fixed in 5 groups of clamping devices.

The relationship between torque and cutting time is shown in Figure 7. The motor speed increases in the starting phase, the average cutting speed increases and the torque increases continuously. The no-load phase is divided into two parts: before cutting and after cutting. The average cutting speed is constant, and the torque remains unchanged. In the cutting stage, the torque increases significantly, while the torque changes accordingly as the branches are fed in batches. In braking phase. the motor decelerates, while the torque increases and then decreases rapidly due to the inertial force of the cutter.

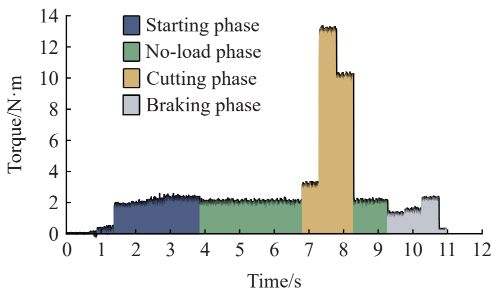


Figure 7 Relationship between torque and cutting time

In order to explore the influence of operating parameters on the cutting effect, ratio of cutting speed to feeding speed k and feeding speed v_f were selected as the test factors, and the cut-off rate n, cutting efficiency w and cutting power P were the target values, in which the cutting power was consumed in the cutting phase. The relevant calculation equations are:

$$k = \frac{v_p}{v_f} \tag{4}$$

$$n = \frac{N_1}{N} \tag{5}$$

$$w = \frac{N_1}{t} \tag{6}$$

$$P = \frac{\omega \int M(t)\mathrm{d}t}{t} \tag{7}$$

where, k is the ratio of cutting speed to feeding speed; v_f is the feeding speed, m/s; n is the cut-off rate, %; N_1 is the quantity of branches that are cut successfully; N is the total quantity of branches; w is the cutting efficiency, stick/s; t is the cutting time, s; $M(t)$ is the torque and cutting time curve function; ω is the cutting system motor speed, rad; P is the cutting power, W.

4.3.2 Single factor test

In order to find out the relationship between each factor and target values, the single factor test was conducted by taking the ratio of cutting speed to feeding speed k and the feeding speed v_f as the test factors, and the cut-off rate n, cutting efficiency w and cutting power P as the target values. As listed in Table 3, each factor test was at 5 levels and repeated 3 times. In the single factor test of the ratio of cutting speed to feeding speed, the feeding speed was 0.6 m/s; the ratio of cutting speed to feeding speed was 1.3 in the single factor test of feeding speed.

Table 3 Factors and levels of single factor test

Levels	Ratio of cutting speed to feeding speed k	Feeding speed v_f/($m\cdot s^{-1}$)
1	0.9	0.4
2	1.0	0.6
3	1.3	0.8
4	1.6	1.0
5	1.9	1.2

4.3.3 Quadratic regression orthogonal test

In order to find the optimal branch feeding speed and ratio of cutting speed to feeding speed, the factors and target values in the single factor experiment were selected to carry out quadratic regression orthogonal test (Table 4). Each group of tests was repeated 3 times. The response surface method was used to analyze the test results, and mathematical models were established to explore the influence of test factors on target values.

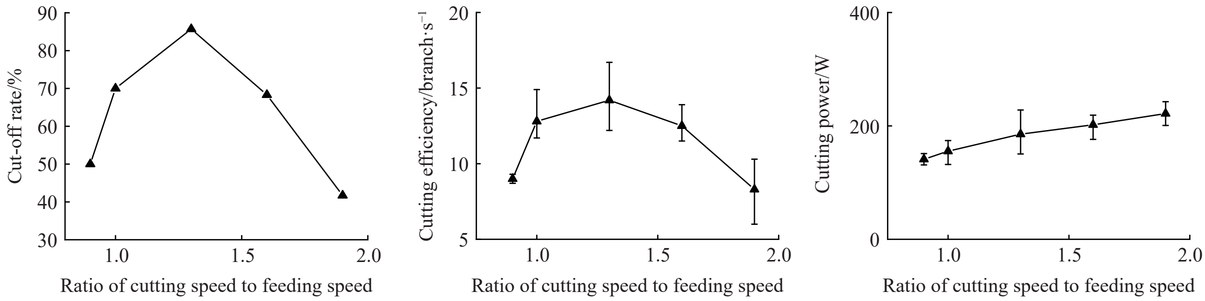
Table 4 Factor coding of quadratic regression orthogonal test

Coding	Ratio of cutting speed to feeding speed k	Feeding speed v_f /$m\cdot s^{-1}$
−1.414	0.88	0.52
−1	1.00	0.60
0	1.30	0.80
1	1.60	1.00
1.414	1.72	1.08

4.4 Results and analysis of single factor test

4.4.1 Ratio of cutting speed to feeding speed

The relationship between the ratio of cutting speed to feeding speed and target values are shown in Figure 8. It can be seen from Figure 8a that the cut-off rate first increases and then decreases with the increase of the ratio of cutting speed to feeding speed. This is because the average cutting speed is small when the ratio of cutting speed to feeding speed is small, and thus a large number of branches are not cut off during the feeding process (Figure 9a), resulting in missing cutting. On the contrary, when the ratio of cutting speed to feeding speed is relatively high, the branches are repeatedly cut, resulting in splitting phenomenon (Figure 9c). Both phenomena lead to fewer branches of intact cutting stubble. The cut-off rate is the highest when the ratio of cutting speed to feeding speed is 1.3, which is 85.7%, and the cutting stubble is complete (Figure 9b). As shown in Figure 8b, the branch feeding speed is the same, so the curve of cutting efficiency and cut-off rate had the same trend. With the enlargement of the ratio of cutting speed to feeding speed, the average cutting speed and the motor speed of the cutting system increase, and the power consumption increases. Even if the cut-off rate decreases, the overall cutting power still increases as the ratio of cutting speed to feeding speed increases (Figure 8c).



a. Cut-off rate b. Cutting efficiency c. Cutting power

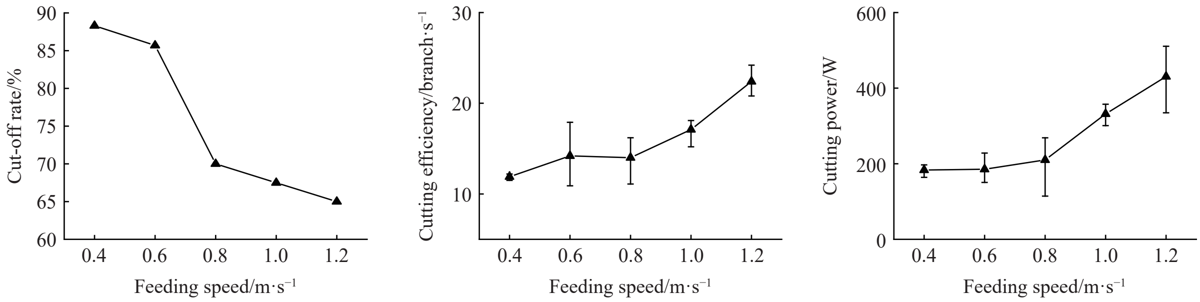
Figure 8 Curves of ratio of cutting speed to feeding speed and target values


a. k=0.9 b. k=1.3 c. k=1.9

Figure 9 Quality of branch cutting stubbles

4.4.2 Feeding speed

The test results of feeding speed and target value are shown in Figure 10. As the feeding speed increases, the cut-off rate decreases (Figure 10a). This is because when the ratio of cutting speed to feeding speed is constant, the average cutting speed increases with the increase of the feeding speed. The faster feeding speed, the more missed branches are cut, and the smaller cut-off rate is. The cutting efficiency increases with the feeding speed, as shown in Figure 10b. The cut-off rate and the cutting time decrease with the increase in the feeding speed, but the overall trend is still increasing because the cutting time has a great influence on the cutting efficiency. In Figure 10b, the increasing trend of cutting efficiency is not obvious when the feeding speed is 0.6 m/s and 0.8 m/s, which is due to the large difference in the cut-off rate. At this time, the cut-off rate has a significant impact on the cutting efficiency, and the cutting efficiency of both is similar. When the feeding speed increases, the average cutting speed and the cutting power increase (Figure 10c). The change of cutting power in the early stage is relatively smoother than that in the later stage. The reason is that when the feeding speed is low in the early stage, the cut-off rate is high, the number of cutting branches is large, and the power consumption relatively increases. In the later stage, with the increase of feeding speed and average cutting speed, the cut-off rate decreases, and the motor speed of the cutting system is the main factor affecting the cutting power.



a. Cut-off rate b. Cutting efficiency c. Cutting power

Figure 10 Curve of feeding speed and target values

4.5 Results and analysis of quadratic regression orthogonal test

The scheme and results of quadratic regression orthogonal test are listed in Table 5. The quadratic polynomial regression fitting of the test results is carried out by using Design-Expert 8.0, and obtain the regression models of cut-off rate, cutting efficiency and cutting power:

$$n = 68.82 + 2.15K - 8.81V + 1.05KV - 11.86K^2 + 3.14V^2 \quad (8)$$

$$w = 14.2 + 0.56K + 1.66V + 0.45KV - 2.42K^2 + 0.66V^2 \quad (9)$$

$$P = 208.64 + 53.06K + 75.68V + 50.05KV + 3.73K^2 + 39.03V^2 \quad (10)$$

where, K is the ratio of cutting speed to feeding speed in quadratic regression orthogonal test; V is the feeding speed in quadratic regression orthogonal test.

The variance analysis of the above models is carried out, and the results are listed in Table 6. Model 1 significant level p = 0.0039, lack of fit p = 0.3381, coefficient of determination (R^2) = 0.8812; Model 2 significant level p = 0.0224, lack of fit p = 0.0778, R^2 = 0.7977; Model 3 significant level p = 0.0002, lack of fit p = 0.0963, R^2 = 0.9489. The significant level p of model 1 and model 3 is less than 0.01, indicating that the model is highly significant; the significance level of model 2 is less than 0.05, the model is significant; the lack of fit of each model is greater than 0.05, indicating that the model has good fit, and the test parameters can be optimized and analyzed. In model 1, the p values of feeding speed and the quadratic term of the ratio of cutting speed to feeding speed are both less than 0.01, indicating that the impact on the cut-off rate is highly significant. Similarly, in model 3, the ratio of cutting speed to feeding speed, feeding speed, the product of ratio of cutting speed to feeding speed and feeding speed, and the quadratic term of feeding speed have a highly significant influence on cutting power. In model 2, the significant level p of feeding speed is less than 0.05, which has a significant impact on the cutting efficiency. The significant level p of the quadratic term of the ratio of cutting speed to feeding speed is less than 0.01, which has a highly significant impact on the cutting efficiency. The significant level p of other items is greater than 0.05, which has no significant effect on target values.

Table 5 Test plan and results of quadratic regression orthogonal test

No.	K	V	n/%	w/(stick·s^{-1})	P/W
1	−1	−1	70.0	12.8	155.4
2	0	0	73.3	15.0	221.3
3	0	0	65.0	13.6	196.4
4	0	0	62.5	12.9	190.0
5	1.414	0	48.3	9.6	265.5
6	−1.414	0	36.7	7.3	172.8
7	0	0	68.3	14.2	205.3
8	0	0	75.0	15.3	230.2
9	0	1.414	56.7	18.3	405.3
10	−1	1	55.0	13.3	194.6
11	1	1	57.5	14.8	441.4
12	1	−1	68.3	12.5	202.0
13	0	−1.414	88.3	10.9	174.2

The surface of each regression model is shown in Figure 11. It can be seen from the figure that with the increase of ratio of cutting speed to feeding speed, the cutting power increases, the cut-off rate and cutting efficiency first increase and then decrease, during which the maximum is around 1.3. When the feeding speed increases, the cutting power and cutting efficiency increase, and the cut-off rate decreases. The test results are basically the same as that of the single factor test.

Table 6 Variance analysis of regression equation

Source	n		w		P	
	F-value	p-value	F-value	p-value	F-value	p-value
Model	10.38	0.0039**	5.52	0.0224*	26.00	0.0002**
K	1.07	0.3355	0.94	0.3643	32.91	0.0007**
V	17.95	0.0039**	8.35	0.0233*	66.94	< 0.0001**
KV	0.13	0.7316	0.31	0.5964	14.64	0.0065**
K^2	28.28	0.0011**	15.46	0.0057**	0.14	0.7180
V^2	1.98	0.2020	1.14	0.3215	15.48	0.0056**
Lack of fit	1.52	0.3381	4.97	0.0778	4.30	0.0963

Note: p<0.01 (highly significant,**), p<0.05 (significant,*), p>0.05 (not significant)

In actual field operations, the premise of high-efficiency and low-power operations is to ensure a high cut-off rate. Therefore, the cut-off rate is the most important among three target values. When analyzing the optimal parameters, set the cut-off rate n≥80%, and get the optimal operation parameter combination as feeding speed 0.55 m/s and ratio of cutting speed to feeding speed 1.29. At this time, the cut-off rate is 84.9%, cutting efficiency is 13.1 and cutting power is 175.7 W.

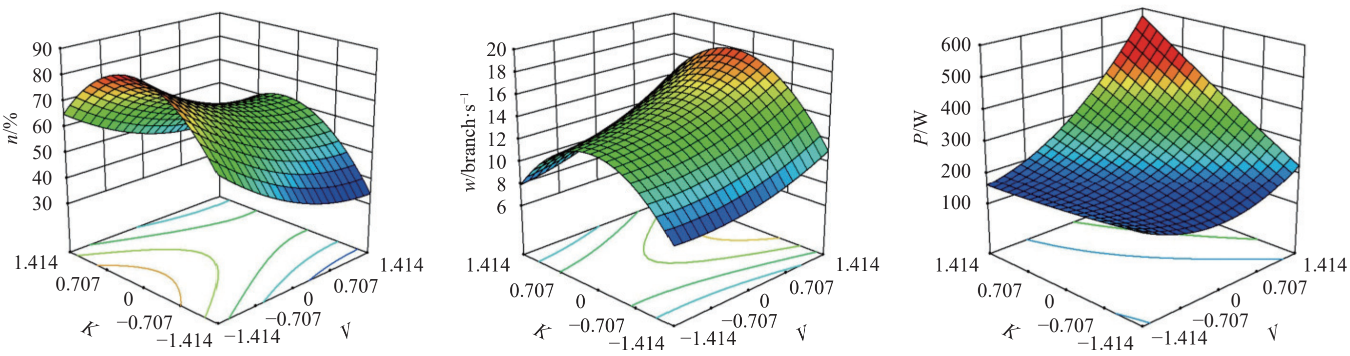


Figure 11 Response surface of target values to interaction of various test factors

4.6 Verifying test

Another three groups of different operation parameters were selected to test and verify the prediction model (group 1: k=1.29, v_f= 0.55; group 2: k=1.20, v_f =0.70; group 3: k=1.40, v_f =0.90). Each experiment was repeated 3 times. The test results are listed in Table 7. The results show that the error between the average measured value and the predicted value of the regression model is less than 7%, which proves that the model is reliable.

Table 7 Results of verifying tests

No.	Measured value			Predictive value			Errors/%		
	n/%	w/(stick·s^{-1})	P/W	n/%	w/(stick·s^{-1})	P/W	n	w	P
1	81.7	13.3	181.8	84.9	13.1	175.7	3.9	1.5	3.3
2	74.6	14.1	179.8	72.2	13.2	171.6	3.2	6.3	4.5
3	66.5	16.3	298.3	64.8	15.2	282.7	2.5	6.7	5.2

5 Experiment of pruning equipment

5.1 Experimental Site

The experimental site was a modern apple orchard (114°33'N, 38°92'E) in Fuping County, Baoding City, Hebei Province, China. The orchard was located in a hilly mountainous area, with Red Fuji as its product. The apple trees were tall spindle apple trees. The average tree age was 3 years, the tree height was 3.5 m, the row spacing was about 4.5 m, and the plant spacing was about 1.5 m. The orchard adopted the ridge cultivation mode, and the ground ridge height was 0.3-0.4 m. The experiment time was October 2021. The experimental site is shown in Figure 12.

5.2 Field experiment

The field experiment site of the pruning equipment is shown in Figure 13. The forward speed of the tractor was 0.55 m/s, and the ratio of cutting speed to feeding speed is 1.29. The experiment instruments were: multi-section luffing pruning equipment, Lovol M604-B tractor, tachometer, tape measure, stopwatch, etc. At present, there is no experiment method and work quality standard for the pruning equipment in China, so the experiment is carried out according to the GB/T 10940-2008[39], which the experiment area was relatively flat and the length was greater than 20 m; the equipment can adapt to the ground undulation, for the semi-suspended pruning equipment, the support surface relative to the tractor wheel rose not less than 200 mm and fell not less than 150 mm. The cutting rate is 96.3%, which is much higher than the simulation experiment value. This is because in the actual field experiment, apple branches are connected to the trunk, the toughness of the pruning end is strong, the feed rate of branches is increased, and the cutting rate is increased. In the experiment, the pruning equipment ran stably and had reliable performance. The experiment results meet the design requirements, improve the pruning efficiency of the orchard and reduce the labor force. We will continue to optimize the pruning equipment in future research, and improve the interchangeability and durability of the equipment.

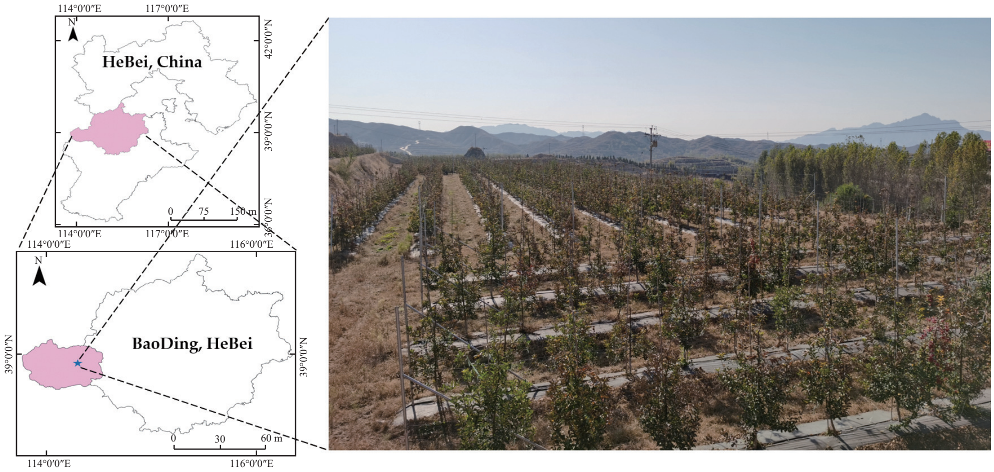


Figure 12 Experimental site

Figure 13 Field experiment of pruning equipment

6 Conclusions

1) In this study, a multi-section luffing apple pruning equipment was designed, and its structure and working principle were described to achieve pruning of high spindle apple trees. Meanwhile, by adjusting the relative positions of the upper, mid and lower cutter, it can also meet the needs of mechanized shaping and pruning of crown shaped fruit trees such as spherical and trapezoidal, and improve the applicability of the pruning equipment. Through the analysis of the key components, the cutting parameters and operating parameters are determined.

2) Taking the cut-off rate, cutting efficiency and cutting power of apple branches as target values, this study explores the effects of ratio of cutting speed to feeding speed and feeding speed on target values through single factor experiment with cutting test bench. The test results show that when the feeding speed is constant, as the ratio of cutting speed to feeding speed increases, the cutting power increases, and the cut-off rate and cutting efficiency increase first and then decrease. When the ratio of cutting speed to feeding speed is small, the phenomenon of missing cutting occurs; on the contrary, the branches are repeatedly cut and resulting in splitting. The cut-off rate is the largest in 85.7% as the value of ratio of cutting speed to feeding speed is 1.3. When the ratio of cutting speed to feeding speed is constant, as the feeding speed increases, the cutting efficiency and cutting power increase, and the cut-off rate decreases. The error between the predicted target value and the average measured target value of the model obtained by quadratic regression orthogonal test is less than 7%, which proves that the model has good fitting and high reliability. The influence of each factor on target values is consistent with the single factor test. When the cut-off rate is greater than 80%, the optimal combination of operating parameters is the feeding speed of 0.55 m/s and ratio of cutting speed to feeding speed of 1.29. Under this combination, the cut-off rate is 84.9%, the cutting efficiency is 13.1, and the cutting power is 175.7 W.

3) Finally, according to the obtained optimal operating parameters, the actual cutting experiment of the pruning equipment in the field was carried out, and the cutting rate was 96.3%, which met the design requirements of the pruning equipment.

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[References]

[1] National Bureau of Statistics. China Statistical Yearbook. Beijing: China Statistics Press, 2021

[2] Huang C W, Cai D X, Wang W Z, Li J, Duan J L, Yang Z. Development of an automatic control system for a hydraulic pruning robot. Computers and Electronics in Agriculture, 2023; 214: 108329.

[3] Li S G, Kang F, Li W B, Zhou S Z, Han X M. Progress advance on pruning mechanization and automation of fruit trees. Journal of Northeast

Agricultural University, 2017; 48(8): 88–96. (in Chinese)
[4] Gai Q G, Zhu X, Shi Q H. The impact of labor migration on agricultural production in China. China Economic, 2014; 13(3): 1147–1170. (in Chinese)
[5] He L, Schupp J. Sensing and automation in pruning of apple trees: A review. Agronomy, 2018; 8(10): 211.
[6] Ma B K, Xu J Z, Sun J S. Consideration for high density planting with dwarf rootstocks in apple in China. Journal of Fruit Science, 2010; 27(1): 105–109. (in Chinese)
[7] Zahid A, Mahmud M S, He L, Heinemann P, Choi D, Schupp J. Technological advancements towards developing a robotic pruner for apple trees: A review. Computers and Electronics in Agriculture, 2021; 189: 106383.
[8] Dorigoni A. Cutting equipment for plant rows. United States Patent, US9295199B2.
[9] Spagnolo F. Rotary blade pruning machine. United States Patent, US6250056B1.
[10] Spagnolo F. SG pruning machine. Australian Patent, AU2006100356A4.
[11] Spencer A. Tree trimming and pruning machine. United States Patent, US00543999A.
[12] Chen K, Li H, Nasihati, Wang M B. Development of 3PJ-1 type gantry pruning machine for grapes. Journal of Chinese Agricultural Mechanization, 2017; 38(2): 28–33. (in Chinese)
[13] Zhang J X, Huang T, Wang M B. Design and experiment of single motor reciprocating grape pruning machine. Transactions of the CSAM, 2021; 52(8): 106–116. (in Chinese)
[14] Long K. Design and experimental research on reciprocating vines pruning machine. Master dissertation. Urumqi: Xinjiang Agricultural University, 2014; 68p. (in Chinese)
[15] Zhang D X, Min L Q, Li Q J, Liu X F, Ren D M, Zhang C Y, et al. Design of PJS-1 two-wing grape pruning machine. Agricultural Equipment and Vehicle Engineering, 2016; 54(2): 77–81. (in Chinese)
[16] Han H M, Zhou Y, Jia S X, Cai W L, Wen X Y. Design of summer wine grape pruning machine. Journal of Agricultural Mechanization Research, 2020; 42(9): 81–86, 92. (in Chinese)
[17] Chang J X, Zhang Y L, Li S J, Zhang W, Ma P Y. Design of citrus trimmer with bilateral and neat trim. Journal of Huazhong Agricultural College, 2019; 38(3): 104–111. (in Chinese)
[18] Liu X C, Liu X F, Zhang L F, Min L Q, Chu Y H, Ren D M. Design and research of wide band combination copying prune machine for new orchard. Journal of Chinese Agricultural Mechanization, 2020; 41(8): 65–71. (in Chinese)
[19] Wu K, Song Y P. Research progress analysis of crop stalk cutting theory and method. Transactions of the CSAM, 2022; 53(6): 1–20. (in Chinese)
[20] McRandal D M, McNulty P B. Impact cutting behaviour of forage crops I. Mathematical models and laboratory tests. Journal of Agricultural Engineering Research, 1978; 23(3): 313–328.
[21] Liu J, Zhao D, Zhao J. Study of the cutting mechanism of oil tree peony stem. Forests, 2020; 11(7): 760.
[22] Chen Y, Gratton J L, Liu J. Power requirements of hemp cutting and conditioning. Biosystems Engineering, 2004; 87(4): 417–424.
[23] Igathinathane C, Womac A R, Sokhansanj S. Corn stalk orientation effect on mechanical cutting. Biosystems Engineering, 2010; 107(2): 97–106.
[24] Igathinathane C, Pordesimo L O, Schilling M W, Columbus E P. Fast and simple measurement of cutting energy requirement of plant stalk and prediction model development. Industrial Crops & Products, 2011; 33(2): 518–523.
[25] Tian K P, Li X W, Zhang B, Chen Q M, Shen C, Huang J C. Design and test research on cutting blade of corn harvester based on bionic principle. Applied Bionics and Biomechanics, 2017; 2017: 6953786.
[26] Du V, Quoc H N, Nguyen H C. Multi-objective optimisation of cutting force and cutting power in chopping agricultural residues. Biosystems Engineering, 2020; 191: 107–115.
[27] Azadbakht M, Esmaeilzadeh E, Esmaeili-Shayan M. Energy consumption during impact cutting of canola stalk as a function of moisture content and cutting height. Journal of the Saudi Society of Agricultural Sciences, 2015; 14(2): 147–152.
[28] Gao Y, Kang F, Kan J, Wang Y, Tong S. Analysis and experiment of cutting mechanical parameters for *Caragana korshinskii* (C. K.) Branches. Forests, 2021; 12: 1359.
[29] Johnson P C, Clementson C L, Mathanker S K, Grift T E, Hansen A C. Cutting energy characteristics of *Miscanthus* x *giganteus* stems with varying oblique angle and cutting speed. Biosystems Engineering, 2012; 112(1): 42–48.
[30] Mathanker S K, Grift T E, Hansen A C. Effect of blade oblique angle and cutting speed on cutting energy for energycane stems. Biosystems Engineering, 2015; 133: 64–70.
[31] Allameh, Alireza, Reza, Alizadeh, Mohammad. Specific cutting energy variations under different rice stem cultivars and blade parameters. Idesia (Arica), 2016; 34(5): 11–17.
[32] Hou J, Bai J, Yao E, Zhu H. Design and parameter optimization of disc type cutting device for castor stem. IEEE Access, 2020; 8: 191152–191162.
[33] Ghahraei O, Ahmad D, Khalina A, Suryanto H, Othman J. Cutting tests of kenaf stems. Transactions of the ASABE, 2011; 54: 51–56.
[34] Huang J C, Zhang B, Tian K P, Liu H L. Design and optimization of the parameters of the key components for reed harvester. International Journal of Agricultural and Biological Engineering, 2022; 15(6): 96–103.
[35] Feng Y L, Yin X C, Jin H R, Tong W Y, Ning X F. Design and experiment of a Chinese chive harvester. Int J Agric & Biol Eng, 2023; 16(2): 125–131.
[36] Kang F, Tong S Y, Zhang H S, Li W B, Chen Z J, Zheng Y J. Analysis and experiments of reciprocating cutting parameters for apple tree branches. Transactions of the CSAE, 2020; 36(16): 9–16. (in Chinese)
[37] Xia J H, Li B Z, Zhang L S. Shaping and pruning technology of high spindle apple tree. Deciduous Fruits, 2013; 45(1): 56–57. (in Chinese)
[38] Zhang D X, Qin X T, Liu X F, Li Q J, Min L Q, Ren D M. Research progress and supporting equipment of orchard branch pruning at home and abroad. China Fruits, 2021; 2: 6–12. (in Chinese)
[39] GB/T10940-2008. Reciprocating mower. China standard, 2008. (in Chinese)