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PARAMETER ANALYSIS AND EXPERIMENT OF CITRUS STALK CUTTING FOR ROBOT PICKING

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KEYWORDS

mechanization, optimisation, parameters, cutting, citrus stem, reciprocating cutting, robot, experiment.

ABSTRACT

In order to provide the basis for the design and control of a citrus picking robot clamp and cutter, and find the optimal combination of cutting parameters, this study used a self-made citrus stem cutting test-bed to study the effects of the citrus stem diameter, blade cutting speed, blade cutting clearance, and tool sliding cutting angle on the peak cutting force of citrus stems through a single-factor experiment. Based on the single-factor test, the blade cutting speed, blade cutting clearance, and tool sliding angle are selected as the influencing factors, and a multi-factor test is carried out with the target of the peak cutting force, and the regression model is established. The results showed that the peak cutting force increased linearly with the diameter of the fruit stalk, decreased with the increase of the blade cutting speed and sliding cutting angle, and first decreased and then increased with the increase of the blade cutting clearance. Through the optimisation analysis of the regression model, it is found that the optimal cutting parameter combination is the blade cutting speed of 40 mm/min, blade cutting gap of 1 mm, tool sliding cutting angle of 20°, and the peak cutting force under this combination is 168.23 N. The deviation between the predicted value of the peak cutting force and the measured value is less than 2%, and the optimisation result of the cutting parameters is reliable. This study provides a theoretical basis for the optimal design and control of the clamping and cutting mechanism of the citrus picking robot.

INTRODUCTION

Citrus is rich in nutrition and is an important cash crop in China (Zhao et al., 2016). At present, citrus is picked manually, which is the most expensive process in its production, leading to high labour intensity, low efficiency, and high costs. Therefore, it is urgent to mechanise and automate citrus harvesting (Bechar & Vigneault, 2016; Miranda et al., 2020).

According to the picking method of the picking robot, the citrus fruit is generally clamped first, and then the fruit and the fruit stalk are separated by pulling or cutting off the stalk (Lu & Sang 2015). Over the years, researchers around the world have conducted extensive research on the mechanical properties of citrus fruits (Lu et al., 2018). However, there are few studies on the stems of the fruits. At present, only Liu Jizhan of Jiangsu University (Liu et al., 2015) has carried out extrusion tests on tomato fruits with different maturity and carried out breaking and tensile tests on tomato stems; Lingxin Bu et al. (Bu et al., 2019) of the Northwest Agricultural and Forestry University adopted four basic picking methods: horizontal traction, vertical stretching, bending and torsion, to analyze the impacts of picking methods on fruit abscission; the physical and mechanical properties of the cutting resistance of cucumber were established. In addition, the material cut by the blade is determined by the cutting quality of the blade (Badiger et al., 2018; Badiger et al., 2018; Basmac et al. 2019). At present, there are no reports on the mechanical properties of citrus stem at home and abroad (Xiong et al., 2018).

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Based on previous studies, this paper took the citrus stem as the research object, simulated the actual cutting condition of the stem on the self-made stem cutting test-bed, selected the blade cutting speed, cutting clearance, and tool sliding cutting angle as the influencing factors, carried out a cutting test on a single stem, and analyzed the influence of various factors on the peak cutting force and cutting effect. The optimal cutting parameters with low power consumption are sought to provide a theoretical basis for the fruit stem cutting design of the end effector of the subsequent picking robot.

MATERIAL AND METHODS

The citrus samples, whose cultivar is "Dafen No. 4", were collected at the orchard of Hunan Academy of Agricultural Sciences on October 1, 2019. The samples are relatively straight citrus fruit stems, with the fresh citrus fruits and redundant transverse branches removed, and no diseases and pests, with a diameter range of 1~5 mm, a length of 120 mm, and a density of 520~540 kg/m^3.

2.2 Test equipment

The self-designed fruit stem shear test-bed used for testing is mainly composed of a shear bench, test system and control system as shown in Figure 1.

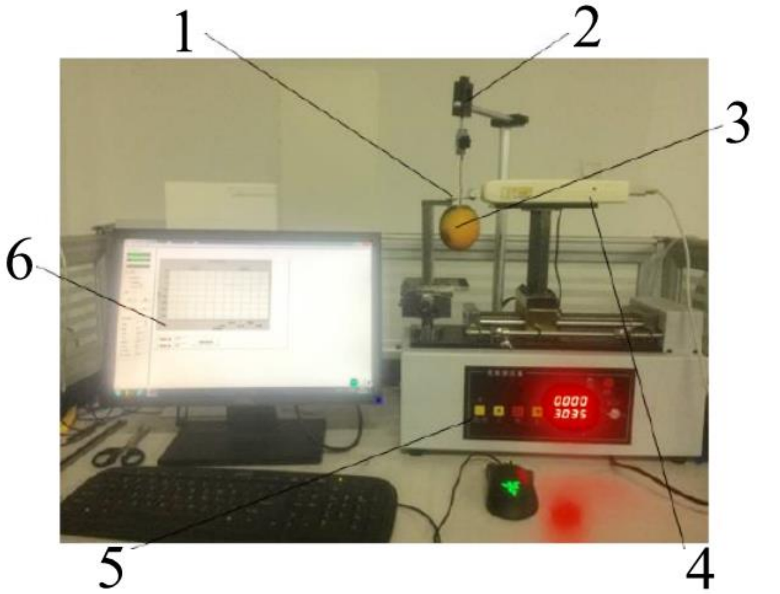

FIGURE 1. Fruit stem shear test bench.

1. Shear blade 2. Adjustable support 3. Test sample 4. Tension reader 5. Wdm-500 tester 6. Computer

In order to determine the influence of various parameters on the shear effect, a special test platform was made, as shown in Figure 1. The test bench below the right side is a WDM-500 electric horizontal test bench, and the upper right side of the test platform is a mobile platform that can provide a test speed of 40–240 mm/min through the lead screw. The mobile platform is equipped with a tension reader produced by Wenzhou Weidu Electronics Co., Ltd., with a maximum load of 500 N and a measurement accuracy of 0.1 N. The front end of the tension reading instrument is equipped with a shear blade through a specially made fixture as the moving knife of the shear device. Above the left side of the test bench is a fixed platform whose height can be adjusted along the vertical direction. Similarly, another shear blade is installed on the fixed platform through a specially made fixture as the fixed knife of the shear device. The blade cutting clearance between the fixed knife and the moving knife can be adjusted by adjusting the height of the fixed platform. The fruit stem as an experimental sample is clamped by an adjustable support placed behind the experimental table. The adjustable support can drive the citrus fruit stem to move and rotate in the radial and vertical directions and rotate around a horizontal axis to provide different fruit handling deflection angles and inclination angles. The tension reading instrument can record the thrust or tension at intervals of 0.01 s, and can be connected with a computer to transmit the experimental data to the computer and directly draw the relationship curve between time and force.

Data collection and process

The tension reader was used to record the measured values of the tension and pressure sensor when the fruit stem cutting test-bed is running at no load and cutting branches. The peak cutting force of the citrus stem was obtained by subtracting the two. At the same time, the process of cutting the fruit stalk with the blade was recorded by the camera. After cutting, the quality of the branch section was observed.

After the pruning test, the cut citrus fruit stalks were sealed and labelled immediately with film to keep them fresh. The moisture content of the test fruit stalk was determined by the drying method, and the sample mass before drying was measured to an accuracy of 0.001 g. The mass was measured again after drying at (103 ± 2) ℃ for 8 h. After that, it was measured every 2 hours. If the mass difference between the two measurements did not exceed 0.002 g, drying was regarded as complete, and the moisture content was calculated. The moisture content of the citrus stalk was 38.7~66.2% during the test (7 days).

Design of experiments

According to the basic scheme of robot harvesting of citrus in a natural orchard environment, the end effector cuts the citrus stalk with a fixed attitude, and the main factors influencing the cutting performance of the end effector are the cutting structure and cutting mode of the blade. This includes the cutting speed of the blade, the gap of the blade, and the sliding cutting angle of the blade.

Single-factor test

To find out how the various factors influence the cutting effect of citrus fruit stem, taking the peak cutting force F as the target value, the citrus fruit stem diameter *D*, blade cutting speed *v*, blade cutting gap *d*, and blade sliding cutting angle *α* were designed. There were 4 groups of single-factor tests. The factors and levels of the single-factor tests are shown in Table 2. The relationship between the citrus stem diameter and peak cutting force was studied more completely (Shi et al. 2019). Therefore, in the single-factor test, the diameter *D* range was 1~5 mm, and 8 levels were set. When conducting other single-factor and multi-factor tests, in order to accurately and quickly obtain the influence of various factors on the inspection index (Johnson et al., 2012), that is, when other parameters remained unchanged, only the value of one parameter at a time was changed to test the influence of this parameter on the shear effect. In order to completely investigate the influence of various parameters on the shear effect, referring to previous studies (Mathanker et al., 2015), the blade cutting speed was controlled by the thrust. Considering that excessive thrust will cause wear on the blade surface and shorten its service life (Basmac et al., 2019), the cutting speed of the blade was chosen as 40~240 $mm \cdot mm^{-1}$; the blade cutting clearance was set to 0.1 ~ 2 mm. The test was repeated 3 times at each level.

TABLE 1. Factors and levels of single-factor test.

Level	Diameter of fruit stem (mm)	Cutting speed ($mm \cdot mm^{-1}$)	Cutting gap (mm)	Sliding cutting angle of blade (°)
1	1	40	0.1	10
2	2	90	0.5	12.5
3	3	140	1.0	15
4	4	190	1.5	17.5
5	5	240	2.0	20

Multi-factor test

Based on the single-factor test results, according to the Box–Behnken principle, taking the peak cutting force as the target value, and taking the blade cutting speed, blade cutting clearance, and blade sliding cutting angle as factors, three-factor and three-level multi-factor tests (Table 2) were designed. Each test was repeated three times. The fruit stem diameter D was 1, 2, 3, 4 and 5 mm, and the branch moisture content was 40.3~43.4%.

TABLE 2. Factors and levels of multi-factor test.

Level	Cutting speed ($mm \cdot mm^{-1}$)	Cutting gap (mm)	Sliding cutting angle of blade (°)
-1	40	0.1	10
0	140	1	15
1	240	2	20

RESULTS AND DISCUSSION

Cutting characteristics of citrus stem

As can be seen from Fig. 2, the overall relationship between the cutting force and displacement of the fruit stalk was nonlinear, but it was similar to the linear relationship at the beginning of cutting. From the overall trend of the figure, the cutting force increased with the increasing cutting displacement, but when the cutting displacement was about 5 mm, the cutting force reached the highest value. When the cutting displacement was greater than 5 mm, the cutting force decreased with the increase of the cutting displacement. When the fruit stalk was completely cut off, the cutting force reached the lowest point. However, as the fruit stalk was cut off and the cutter touched the backing plate, the cutting force increased. It was found that under different cutting conditions, the variation of the cutting force of citrus stem with displacement was similar.

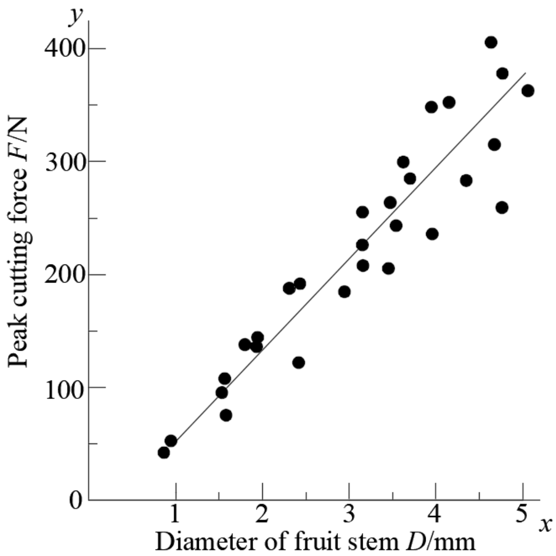

FIGURE 2. Relationship between branch diameter and peak cutting force.

As shown in Fig. 2, when the blade cutting speed, blade cutting clearance and blade sliding angle were certain, the peak cutting force had an obvious linear relationship with the branch diameter. The peak cutting force increased with the increase of the citrus stem diameter.

Analysis of single-factor test results

Effect of cutting speed on peak cutting force of citrus stem

According to the motor configuration of the self-made shear test-bed, five shear speeds of 40, 90, 140, 190, and 240 mm/min were selected. The other values of the basic quantity remained unchanged during the test. The fruit stem diameters *D* were 1, 2, 3, 4, and 5 mm, the blade cutting gap *d* was 1 mm, and the blade sliding cutting angle *α* was 20°.

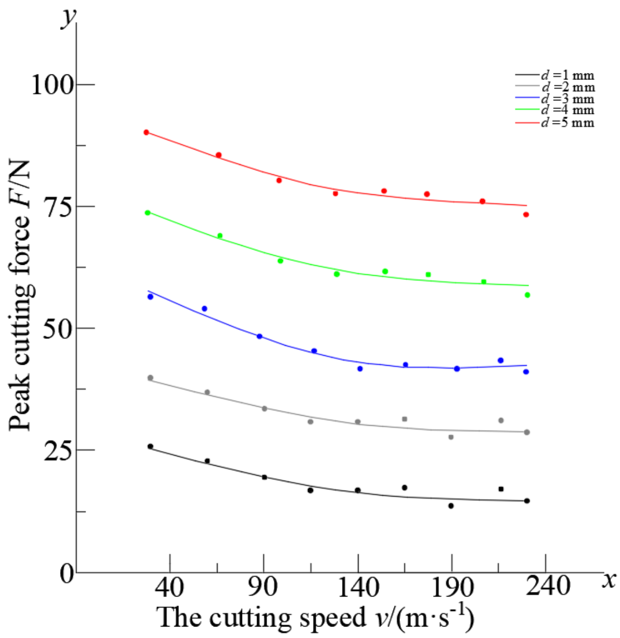

FIGURE 3. Influence of different cutting speeds on cutting performance.

The test results of the peak cutting forces and blade cutting speeds are shown in Fig. 3. The relationship between the peak cutting force and blade cutting speed was quadratic polynomial fitting, and decreased gradually with the increase of the average cutting speed (Koklu et al. 2019). This is because, with the increase of the cutting speed, the extrusion stage of the citrus stem before cutting was shortened, resulting in the gradual decrease of the peak cutting force. However, when the cutting speed continued to increase, the extrusion stage of branches was shortened slowly or was even not obvious, resulting in a relatively gentle decreasing trend (Zhao et al., 2016a).

Effect of blade cutting clearance on peak cutting force of citrus stem

The clearance of the blade is one of the important standards for making the end effector. During the test, the clearance between the fixed blade and the moving blade started from 0.25 mm, and the test was carried out every time the clearance increased by 0.25 mm. Five blade cutting clearances of 0.5, 1, 1.5, 2, and 2.5 mm were selected. The other values of the basic quantity remained unchanged during the test. The fruit stalk diameters *D* were 1, 2, 3, 4, and 5 mm, the blade cutting speed *v* was 140 mm/min, and the blade sliding cutting angle *α* was 20°.

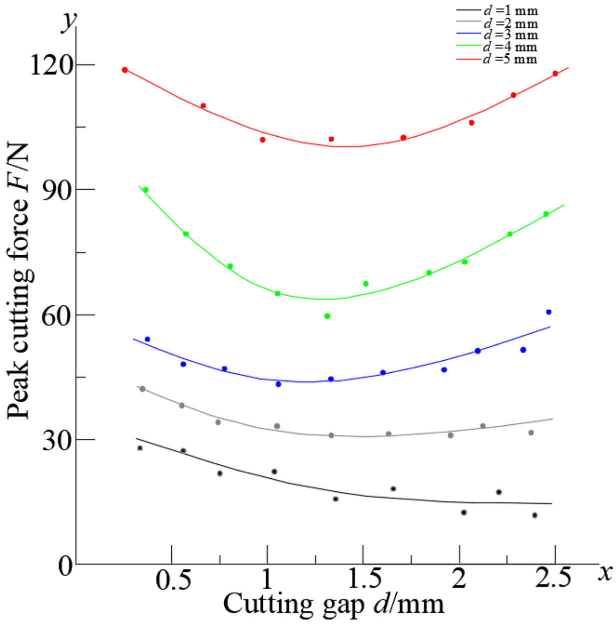

FIGURE 4. Influence of different cutting angles on cutting performance.

According to the test results, when the shear speed was high, the peak shear force first decreased and then increased with the increase of the blade cutting gap (Fig. 4). When cutting fruit stalks with different diameters with different blade cutting gaps, and when the size of the blade cutting gap was close to but slightly smaller than the diameter of the fruit stalks, the shear success rate of the fruit stalks began to decline. When the size of the blade cutting gap was the same as the diameter of the fruit stalks, the shear success rate was low. Only when the cutting clearance of the blade and the diameter of the fruit stem were the same, the peak cutting force was the smallest, about 122.86 N.

Effect of blade sliding cutting angle on peak cutting force of citrus stem

According to the sliding cutting principle (Hampson et al., 2002), the cutting force decreased with the increase of the sliding cutting angle. When the sliding cutting angle is greater than 20°, the branches will slip outward, so the cutting force was reduced with the tool sliding cutting angle *α* set to 10~20°. For other single-factor tests, the sliding cutting angle was 20° to ensure a small peak cutting force. Five sliding cutting angles of 10, 12.5, 15, 17.5 and 20° were selected. The other values of the basic quantity remained unchanged during the test. The fruit stem diameters *D* were 1, 2, 3, 4 and 5 mm, the blade cutting speed *v* was 40 mm/min, and the blade cutting clearance *d* was 1 mm.

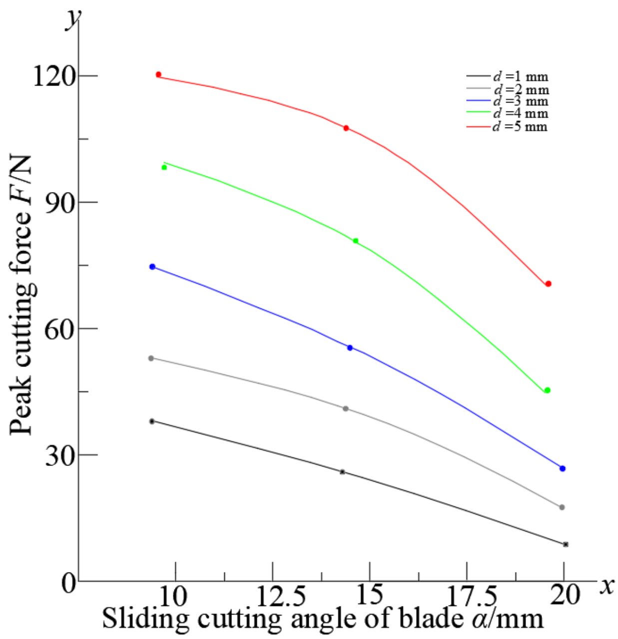

FIGURE 5. Cutting performance under different diameters of fruit stem.

The relationship between the peak cutting forces and the tool sliding angles is shown in Fig. 5. The peak cutting force decreased with the increase of the tool sliding angle. The reason was that the tool edge was serrated in the microstate, and the sliding cutting angle became larger, which increased the amount of slip of the branches along the length of the tool edge, enhancing the cutting effect of the serrated edge on the branch fibres, so the required peak cutting force was reduced.

RESULTS AND ANALYSIS OF MULTI-FACTOR ORTHOGONAL TEST

Multi-factor test results

From the above single-factor test results, it was found that the cutting force of citrus fruit stem was mainly related to the diameter of the citrus fruit stem, blade cutting speed, blade cutting clearance and tool sliding cutting angle. Considering that there were too many parameters involved and that the levels of each factor were different, a quadratic polynomial regression fitting was carried out on the test results in Table 4, using Design-Expert 8.0 software to obtain the peak shear force prediction model, and the following results were obtained:

$$F=92.45+0.1X_1-0.76X_2+0.13X_3-0.65X_1X_2-0.089X_1X_3-1.28X_2X_3-1.79X_1^2-1.04X_2^2-1.08X_3^2$$

TABLE 3. Results of cutting force orthogonal test.

Serial number	Level of factor			Peak cutting force
	X_1/((mm/s)	X_2/°	X_3/mm	F/N
1	0	0	0	155.66
2	1	0	1	128.88
3	1	-1	0	159.64
4	1	1	0	148.23
5	1	0	-1	150.89
6	- 1	0	1	121.72
7	0	0	0	157.72
8	0	0	0	168.23
9	-1	-1	0	50.70
10	-1	1	0	100.92
11	0	1	1	108.23
12	0	-1	-1	99.03
13	0	0	0	108.92
14	0	-1	1	103.27
15	0	1	-1	92.00
16	0	0	0	91.80
17	-1	0	-1	91.65

NOTE: X_1 is the blade cutting speed; X_2 is the cutting gap; X_3 is the sliding cutting angle of the blade.

Analysis of variance

Regression analysis of variance was carried out for the multi-factor test results and the peak cutting force prediction model. The results are shown in Table 4. The results showed that the significance level *P* value of the model was 0.0001 (less than 0.01), indicating that the model was very significant. The *P* value of the mismatch term was 0.3034, which showed that the model had good fitting and could optimise the optimal cutting parameters.

TABLE 4. Variance analysis of regression equation.

Sources	Sum of squares	Freedom	Mean square	*F* value	Significance level *P*
Model	42147.78	9	5122.84	21.23	0.0001**
X_1	11021.14	1	11248.25	38.65	<0.0001**
X_2	28.24	1	25.58	0.18	0.57732
X_3	18792.36	1	18792.36	108.52	<0.0001**
X_1X_2	1.83	1	1.89	0.01	0.8721
X_1X_3	333.14	1	333.14	1.66	0.2521
X_2X_3	321.21	1	321.21	1.75	0.2487
X_1^2	66.85	1	66.85	0.25	0.6248
X_2^2	6324.52	1	6324.52	27.85	0.0008**
X_3^2	1868.32	1	1868.32	12.35	0.0158**
Residual	1385.61	7	197.94		
Lack of fit	768.24	3	256.08	1.25	0.2520
Pure error	521.42	3	173.80		
Total	38842.26	16			

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

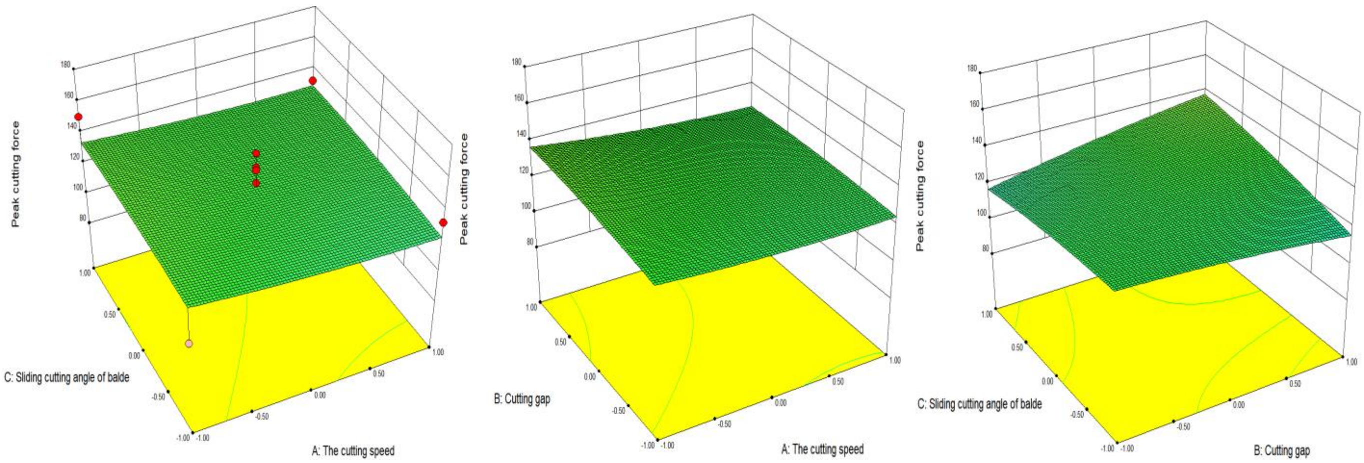

FIGURE 6. Response surface of peak cutting forces to the interaction of various test factors.

The model determination coefficient was R^2 = 0.9667, indicating that 98.71% of the change of peak cutting force comes from the selected factors. The significance level *P* values of the quadratic terms of the blade cutting speed, tool sliding angle and blade cutting clearance were less than 0.01, so they have a significant impact on the peak cutting force. The significance level *P* of the quadratic term of the tool slip angle was less than 0.05, meaning that it has a significant impact on the peak cutting force. The *P* values of the other items were greater than 0.05, and they therefore had no significant effect on the peak cutting force. The analysis showed that the main and secondary factors affecting the peak cutting force of citrus stem are the tool sliding cutting angle, average cutting speed and cutting clearance.

Through stepwise regression analysis, the non-significant items in the formula were eliminated and the significant items were retained (P < 0.05). The simplified model was as follows:

$$F=85.45+0.1X_1-0.76X_2+0.13X_3-1.79X_1^2-1.04X_2^2-1.08X_3^2$$

The influence of the interaction of various factors on the peak cutting force is shown in Fig. 6. The peak cutting force decreased with the increase of the blade cutting speed or tool sliding angle. With the increase of the blade cutting gap, the peak cutting force first decreased and then increased. When the blade cutting gap was about 1.5 mm, the peak cutting force reached the minimum, which is consistent with the relevant conclusions of the single-factor test.

CONCLUSIONS

1) In this study, a self-made fruit stem cutting test-bed was made. Taking the peak cutting force of citrus fruit stem as the target value, the relationship between the citrus fruit stem diameter, blade cutting speed, blade cutting clearance,

tool sliding angle, and peak cutting force was explored through single-factor tests. The results showed that the peak cutting force of citrus stem increased linearly with the diameter of the stem. When the blade cutting speed was 40 mm/min, the peak cutting force decreased with the increase of the cutting speed. The greater the cutting speed, the smoother the branch section was. When the blade cutting gap was 0.1~2.0 mm, the peak cutting force decreased first and then increased. The peak cutting force reached the minimum when the blade cutting gap was 1.5 mm, and the cutting gap had little effect on the quality of the branch section. When the tool slip angle was 10~20°, the peak cutting force decreased with the increase of the slip angle.

2) The error between the predicted peak cutting force and the measured peak cutting force was less than 4%, which showed that the model had a good fitting and high reliability. The influence of each factor on the target value was consistent with the single-factor test. The primary and secondary order of the influence on the peak cutting force were: tool sliding cutting angle, blade cutting speed, and blade cutting clearance. The optimal cutting parameter combination within the test range was the blade cutting speed of 40 mm/min, blade cutting gap of 1.5 mm, and tool sliding angle of 20°. When the diameter of the citrus stalk being cut was 1 mm, the minimum peak cutting force under this combination was 168.23N.

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