Tensile mechanical properties of greenhouse cucumber cane

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Abstract: To obtain the mechanical properties of greenhouse cucumber cane, tensile and shear properties of the greenhouse cucumber cane were studied by using computer-controlled electronic universal testing machine and homemade cutting test bench, respectively. Firstly, the root, middle and head of cucumber cane were subjected for tensile tests. The tensile stress-strain curves showed that the root of cumber cane presented the characteristics of plastic material, while the middle and head showed the characteristics of brittle material. The average tensile strength of root, middle and head of fresh cucumber cane were 7.35 MPa, 6.30 MPa and 4.68 MPa, respectively. The average elastic modulus of root of fresh cucumber cane was 280.58 MPa, which was much greater than the middle and head with average elastic modulus of 198.81 MPa and 137.22 MPa, respectively. A pendulum impact cutting test-rig and a cutting force measurement system composed of a cantilever weigh sensor, a high frequency DAQ card and motion control card were developed. The cutting mechanical property experiments of different parts of greenhouse cucumber cane were carried out, and the continuous curves of cutting force were measured. The single factor test for cross-sectional area, cutting speed, cutting tool type and manner were analyzed. The results indicated that the peak cutting force increased approximately linearly with the increasing of cutting sectional area, but decreased gradually with the increasing of cutting speed. In the same conditions, the cutting force could be reduced by using straight blade cutting tool and ramp cutting way. Through the multifactor interaction impact test of the cutting way, the blade type and the cutting speed, it was found that the corresponding *F*-value of the three factors were 21.316, 49.141 and 0.222, which suggests that the blade type is the most significant factor for the cutting force.

Keywords: cucumber cane, mechanical properties, modulus of elasticity, tensile strength, cutting force
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1 Introduction

Straw is the world's largest number of agricultural products, and is also an important biological resource for comprehensive utilization[1-3]. The total horticultural facilities area in China was 38 600 km^2 in 2012, ranking first in the world[4]. A large amount of straw was produced from horticultural facilities. Cucumber cane is

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one of the main horticultural crops, which contents of high toughness and moisture. Due to the difficulties dealing with straw crushing and composting process, cucumber cane was discarded in the fields, roadsides, rivers and lakes[5-7]. Large amount of cucumber canes not only are a waste of valuable resources, but also lead to large area of agricultural pollution, and serious plant diseases and insect pests by the root knot nematode, fungal infection in horticultural facilities. How to utilize the cucumber cane becomes one of the problems that must be solved during the sustainable development of facilities horticulture.

Mechanical properties of the cane including tensile properties, bending properties, shear properties and compression characteristics[8-10], the main indicators related to cutting are tensile strength, elastic modulus and cutting force, etc.[11]. Chattopadhyay and Pandey[12] determined the mechanical properties of sorghum stalks using a universal testing machine. The results showed that the mechanical strength and energy consumption of sorghum stalk in shear and compression increased when the knife bevel angle increased from 30° to 70°, but they were found decreasing with an increase of loading rate. Mathanker et al.[13] investigated the effect of cutting speed and blade oblique angle on cutting energy for energy-cane stems. They found that the specific cutting energy increased with cutting speed and optimization of cutting speed and blade oblique angle could result in significant savings in cutting energy, simultaneously improving the quality of cut. Igathinathane et al.[14] dealt with the determination of the effect of dry corn stalk orientation with respect to cutting element and quantifying the possible cutting energy reduction. The results showed that the parallel orientation (along grain) compared to perpendicular (across grain) produced a significant reduction of the cutting stress and the specific energy to one-tenth or better for internodes, and to about one-fifth for nodes. The corn straw chopping orthogonal test was carried by Wu et al.[15], they found that the slip ratio cut is average 4.34 m/s lower than cutting speed; the power consumption of cutting off two straws is about 37 N·m larger than single. Results presented by Ma et al.[16] showed that root of wheat straw was the most easily cutting parts. The more straws, the larger cutting velocity needed. The blade thickness had no significant effect on the cutting speed. The compressing, stretching, bending, shearing destruction stress and elastic modulus of mature stems at the bottom edge of the reed stalk were tested by Cao et al.[17], and they observed that the maximum destruction stress and elastic modulus were essential in analyzing the stress-strain distribution during the process of cutting the reed stem. Öztürk and Esen[18] studied physico-mechanical parameters (bulk density, angle of internal friction, true density, static coefficient of friction) of three corn varieties widespread cultivated in Turkey to determine the structural designing parameters of silo and bins used for storage. In order to determine the relationship between tensile strength and diameter of trees, tensile tests on roots 0.2-12.0 mm in diameter of three conifer and two broadleaf species were carried out by Genet et al.[19]. They reported that cellulose was responsible for tensile strength in wood due to its microfibrillar structure and a significant power relationship existed between tensile strength and root diameter, with a sharp increase of tensile strength in roots with diameters less than 0.9 mm. Researches that mentioned the mechanical properties of the straw mostly focused on corn, rice, wheat straw, et al., rarely discussed cucumber cane with winding characteristic, and mostly considering the influence of single factor, rather than the interaction influences of the various factors.

It would be advantageous to assess machine performance by taking into account the crop properties at the design stage instead of through actual machine tests, especially from the viewpoints of cost reduction and the shortening of the development period[20]. In this research, stretching test of greenhouse cucumber cane was carried out. The tensile strength and elastic modulus of the root, middle and head of the canes were obtained. To comprehensive study the index of cutting force, the single factor cutting test and multi factors interaction cutting tests for moisture content, we analyzed cross-sectional area, cutting speed, cutting tool type and manner. It can provide a theoretical support for designing and manufacturing of high-efficiency and low power horticultural straw cutting machinery.

2 Materials and methods

2.1 Sample collection

The test materials is mature Jasper No.2 cucumber cane derived from the Jiangsu University greenhouse, collected on November 29, 2011. The randomly selected samples were those with no mechanical damage, no pests and diseases of plants from greenhouse cucumber cane. According to the provisions of GB/T228.1-2010 for the type of atypical sample, the length of each sample was determined to be 120 mm. The specimens at both ends of each 10 mm were used for clamping. The bottom sample was 120 mm cut from the root end of cucumber cane stem using a scalpel, and the top sample was 120 mm cut from the top end of it. The remaining part of the central was as a specimen every 120 mm. Cross-section of the cucumber cane is irregular polygon, which can be approximately equaled to the rectangle. The width and thickness of samples were measured by vernier caliper, accurate to 0.1 mm. According to GB/T1931-2009, the samples were dried 10 h using the DZF-6020 type vacuum drying box under 40ºC and vacuum conditions. The moisture content was calculated according to the sample weight before and after drying with an accuracy of 0.001 g.

2.2 Tensile test and method

Tensile test was carried out on a WDW30005 microcomputer control electronic universal testing machine, as shown in Figure 1. When the experiment was carried out, in order to prevent straw slipping from the clamp, a clamping head with rubber pad stuck to the surface was used, and the two ends of the sample was clamped between the testing machine. Selecting the 20 mm/min loading speed to apply tension until the cane was snapped. When the cane breaks and the crack is not on the cane under jig, the test can be considered as successful. The test was repeated 50 times. The map of load *F*-displace could be recorded on the computer by tracing point, and the coordinates of each point were saved as Excel file. The *t*-test and regression analysis of the SPSS software were used to analyze the tensile strength.

The elastic modulus *E* of cucumber cane was calculated according to Hooke law:

$$E = \frac{\sigma}{\varepsilon} \tag{1}$$

where, E is the elastic modulus, MPa; σ is stress, MPa; ε is strain.

Tensile strength was calculated by:

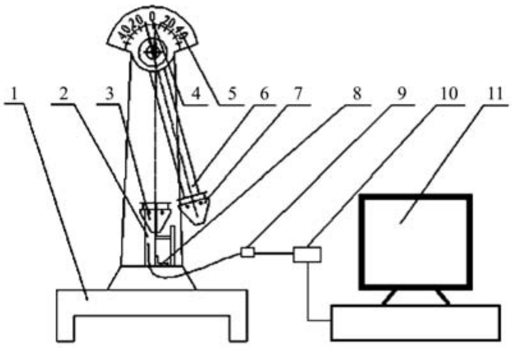
$$\sigma_{\max} = \frac{F_{\max}}{A} \tag{2}$$

where, $\sigma_{\max}$ is the tensile strength, MPa; $F_{\max}$ is the maximum load in the test, N; A is the cross section for the fracture area, mm^2.

Figure 1 Electronic universal testing machine

2.3 Cutting test and method

Cutting test was carried out on the self-made pendulum type cutting test-rig and a cutting force measurement system composed of the ABT-130 cantilever beam weighing sensor (range of 10 kg), Advantech 812PG data acquisition card and USB1010 motion control card were developed[21]. Procedures were programmed by using the Labview language, and its structure and principle are shown in Figure 2. A fixed knife with a cantilever force sensor mounted on a movable support works together with the knife at the end of the pendulum to realize cutting process. Cutting speed can be adjusted by changing the pendulum swing angle and the cutting force can be measured by the sensors. Since the signal of cutting force is extremely weak, it needs to be amplified 1000 times by a special filter amplifier to convert to the standard analog voltage signal of ±5 V (error less than 0.5%). Signals of the sensor were transmitted to the industrial computer by the high-frequency data acquisition card. Labview program was used for real-time display of the cutting force variation process and saved as the Excel format in the industrial computer for subsequent data processing. To improve the measurement precision, the 10 times repeat testing values are averaged as the final result in each group.



Note: 1. Installation base 2. Sensor 3. Fixed knife 4. Pointer 5. Dial 6. Pendulum 7. Knife 8. Mobile support 9. Apecial filter amplifier 10. High-frequency data acquisition card 11. Industrial computer

Figure 2 Structure diagram of single pendulum cutting test-rig

According to the law of conservation of energy, the following equation can be obtained in the pendulum type cutting test-rig:

$$mgh = \frac{1}{2}mv^2 \tag{3}$$

where, m is the weight of the pendulum, kg; g is the acceleration of gravity, 9.8 m/s^2; h is the vertical height difference of knife between swing angle of 0° and α, m; v is cutting speed, m/s.

According to the geometry relation of the pendulum

$$h = (1 - \cos\alpha)L \tag{4}$$

where, L is the length of pendulum, m.

Substitute Equation (4) into Equation (3), the cutting speed can be obtained:

$$v = \sqrt{2gL(1 - \cos\alpha)} \tag{5}$$

Swing angles were selected as 20°, 30° and 40° in this research, and corresponding cutting speeds were 1.4 m/s, 2.1 m/s and 2.8 m/s, respectively. The cutting object was 20 mm^2 cross-sectional area of cucumber cane.

In order to investigate the effects of different tool types on cutting force of the cucumber cane, factors of straight edge blade, hammer type blade and the serrated blade were chosen for test. To keep the cutting speed in 1.4 m/s, each test places the pendulum to swing angle of 20°. Similar thickness, similar moisture content, and same maturity cucumber canes were chosen as test material.

Previous study showed that the cross-sectional area of wheat influenced the cutting force and cutting power[22]. In order to study the influence of cross-sectional area of cucumber cane on cutting force, the straight blade type cutting blade with 1.4 m/s cutting speed was selected to test five cross-sectional areas of cucumber cane, i.e. 5 mm^2, 10 mm^2, 15 mm^2, 20 mm^2 and 25 mm^2 at different parts (root, middle and head) of the same cross-sectional area.

The longitudinal and transverse mechanical properties of cucumber cane are not same, namely anisotropy of straw, so the knife cutting cucumber cane with different angles will have different effects on the cutting resistance of cane. Taking the 20 mm^2 cross-sectional area of the cucumber cane as the cutting object, using straight edge blade, tests with 1.4 m/s cutting speed were carried out under three different cutting modes , i.e. transverse cutting, oblique cutting and ramp cutting, on different positions of cucumber cane.

In actual cutting process, factors will have interaction effect on the cane cutting resistance. Therefore, three factors of cutting way (A), blade type (B) and the cutting speed (C) with three levels each were selected in the experiment, namely the $L_9(3^4)$ orthogonal experiment, and with 10 times repeat in each group. The cutting forces statistical analysis was carried out to find the most significant influencing factors, and the best combination of factor levels.

3 Results and discussion

According to test determination results, water contents of different parts of the cucumber cane are not the same, the average contents at roots, middle and head were 22.22%, 25.13% and 40.36%, respectively. Distributions of moisture have significant differences in different parts of the cane, and the increasing trend is presented from the roots to the head of the cucumber cane. Water content of the head is about two times of the root. This is probably because the degree of lignifications at the root is relatively high and the head is mainly composed of some new organs with high moisture content.

3.1 Tensile test and results

Figure 3 shows the axial tensile stress-strain curves for the average cross-sectional area of the 4.49 mm^2 root, 17.63 mm^2 middle and 14.16 mm^2 head of the cucumber cane, respectively. The tension increases gradually until the cane is broken. In this process, in addition to a small part of slip start tightening phase, the curves of the head and root are approximately linear, in line with the characteristics of brittle materials, as shown in Figure 3; and the central sample generally experienced four stages namely elastic, yield, hardening and fracture, in line with the characteristics of plastic materials.

The test results were analyzed by using SPSS data analysis software, as shown in Figure 4.

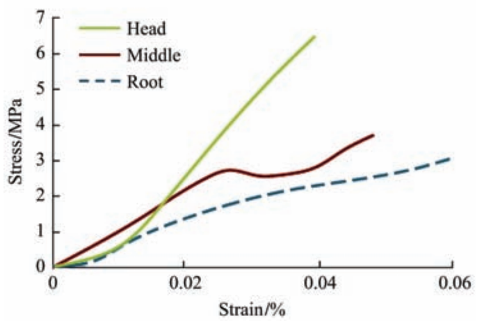


Figure 3 Stress-strain diagram of cucumber cane

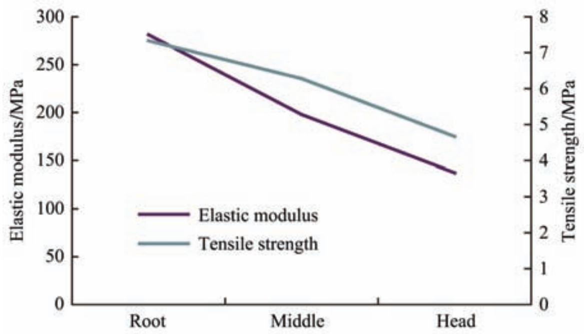


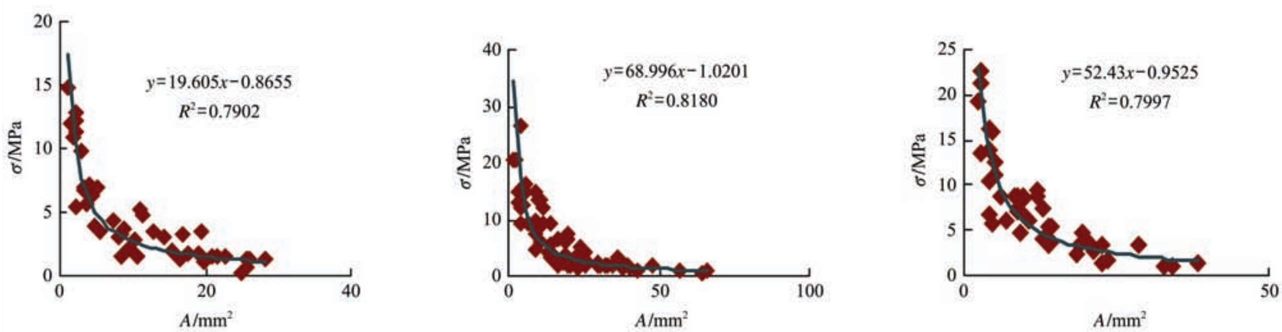
Figure 4 Tensile strength and elastic modulus at different parts

1) The average tensile strength of the root, middle and head part of cucumber cane stalk are 7.35 MPa, 6.30 MPa and 4.68 MPa, respectively, and the average elastic modulus are 280.58 MPa, 198.81 MPa and 137.22 MPa, respectively. It can be found that the ability to resist deformation decreased gradually from the root to the head.

2) The independent samples t-test results of the tensile strength for root and head, root and middle, head and middle part of cucumber cane show that concomitant probability of the tensile strength F-values $p\leq0.05$, so it rejects the null hypothesis of the equal variances is rejected; concomitant probability of t statistic values $p\leq0.05$ (0.0060, 0.0001 and 0.0030, respectively), so the null hypothesis of the t-test is rejected. It can be considered that tensile strength in different parts of the cucumber cane had a significant difference.

3) Mean square errors of tensile strength and elastic modulus of cucumber cane in different parts are large, reflecting that the difference is big between individuals.

The tensile strengths of different parts and different cross-sectional areas of cucumber cane are different, so the cross-sectional area and tensile strength were curve fitted and regression analyzed. The results show that the power function model has good fitting degree, and regression coefficient R of the head, the middle and the root fitting equations are 0.8889, 0.9083 and 0.8986, respectively. Relationship between tensile strength and cross-sectional area of cucumber cane is shown in Figure 5. It shows that the tensile strength at different parts of cucumber cane in power function decreases with the increase of cross-sectional area, but the decreasing function are not same. The results provide basic data for the selection of cutting force, cutting speed and other technical parameters for straw cutting machine.



a. Head b. Middle c. Root

Figure 5 Relationship between tensile strength and the cross-sectional area

3.2 Cutting test and results

3.2.1 Single factor test

1) Cutting speed

Cutting tests were carried out on different positions of cucumber cane, and the test results are shown in Figure 6. Cutting force of the same positions on cucumber cane decreases with increase of cutting speed and the biggest decline is in root, followed by the middle, decreasing in head is gentle. Under the same cutting speed, the cutting forces of the root, middle, head decreased progressively. Therefore, to reduce cutting force, the cutting speed should be increased when selecting the cutting force of cutting machinery.

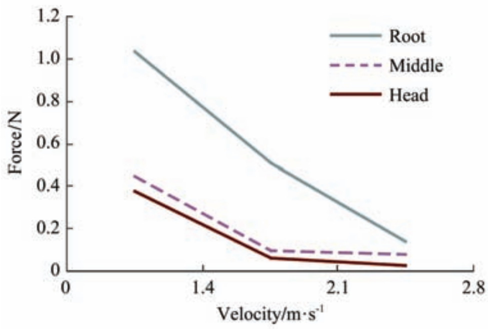


Figure 6 Influence of different cutting speeds on cutting forces

2) Tool type

Cutting experiment on different positions using transverse cutting way was carried out and the results are shown in Figure 7. It can be found that while other conditions are the same, the hammer blade cutting resistance is the biggest in three different blade types, followed by the serrated blade, and the straight edge blade is the most labor-saving. As can be seen from the graph, in the root cutting test, the influence of hammer type blade on cutting forces is the biggest, while the serrated blade and straight edge blade have little effect on cutting force of the middle and head cutting test, but it was found that when root of cucumber cane was cut using hammer type blade, sometimes a drag and drop phenomenon appeared, which is unfavorable to cutting. This is because the hammer type blade does not have a cutting edge, so the cutting mainly depends on the impact force. Under the same experimental conditions, greater cutting force is needed to finish cutting. Therefore, without considering the wear condition, relative to the hammer type blade, it should be priority to select straight edge or serrated blade.

3) Cross-sectional area

The effect of different cross-sectional areas on cutting forces is shown in Figure 8. The results show that with the increase of cross-sectional area, the cutting forces increases gradually. When the cross-sectional area of cane is 5 mm^2, the cutting forces of three different positions almost the same. When the cross-sectional area is greater than 5 mm^2 but less than 10 mm^2, the cutting forces have the similar variation trend; but when the cross-sectional area is greater than 10 mm^2, the cutting force of the root has the biggest change, and the changes of head and the middle are relatively smooth.

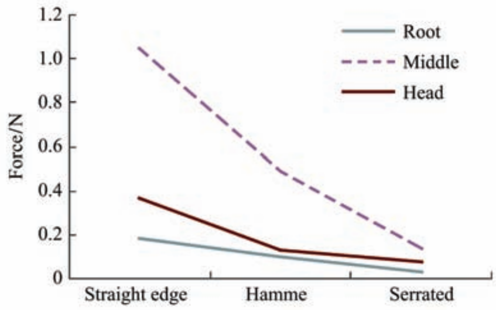


Figure 7 Influence of different blade types on cutting forces

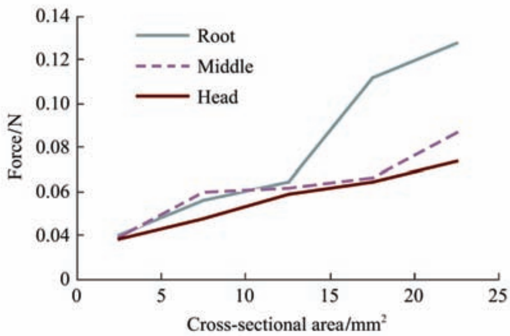


Figure 8 Influence of different cross-sectional areas on cutting forces

4) Cutting mode

The influences of different cutting modes on cutting forces are shown in Figure 9. The results show that the cutting resistance is the biggest under the mode of transverse cutting, oblique cutting is secondary and ramp cutting is the most labor-saving way. In the same cutting position, cutting resistance under transverse cutting mode increases about 60% than ramp cutting mode, and oblique cutting mode increases around 20% than ramp cutting mode. Therefore, under the same conditions, the ramp cutting mode should be selected.

During the test process, it was also found that the transverse cutting mode made cucumber cane along the fiber longitudinal rupture directly, the cutting section was neat and smooth. When using oblique cutting mode, with the increase of oblique angle, the cross-sectional area of cane incision also increased, the outer skin away from the incision side of the cane appeared uneven, cutting quality decreased. Therefore, oblique cutting mode could help to reduce the cutting force, but the angle should not be too large to preventing the decline of cutting quality. Similarly, when using the ramp cutting way and about 30°cut angle, outside skin tear phenomenon also appeared at cane cutting section away from the incision.

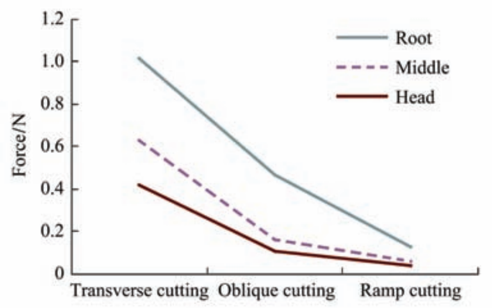
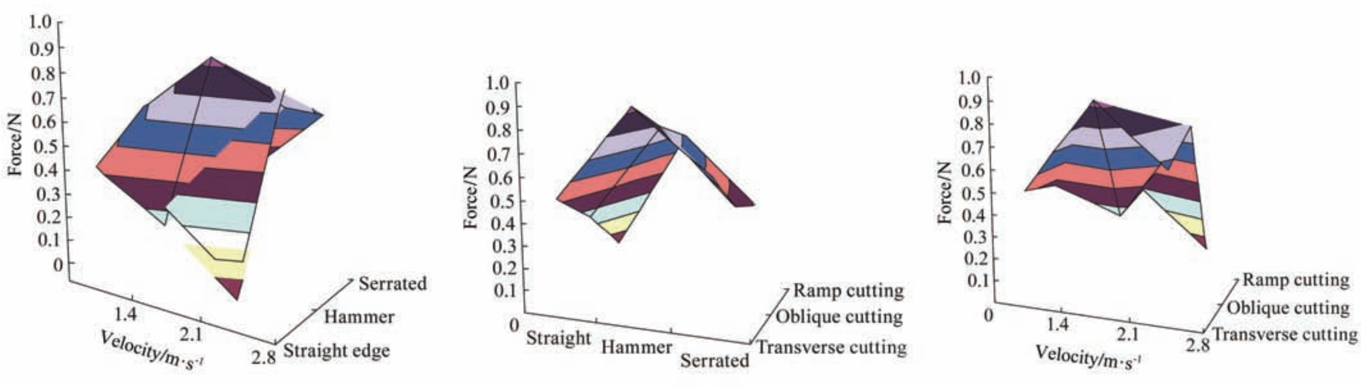


Figure 9 Influence of different cutting modes on cutting forces

3.2.2 Orthogonal test

Figure 10 shows the cutting force under the interactive effects of blade type and cutting speed, blade type and cutting mode, cutting speed and cutting mode. As Figure 10a shows, while the cutting speed is 2.8 m/s, straight edge blade cutting force is minimal; while cutting speed is 2.1 m/s, the hammer blade cutting force is maximal. As Figure 10b shows, the cutting force is minimal when using the straight edge blade and ramp cutting mode, and maximal when using the hammer blades and transverse cutting mode. As can be seen from Figure 10c, while the cutting speed is 2.8 m/s with the ramp cutting mode, cutting force is minimal; while the cutting speed is 2.1 m/s with the transverse cutting mode, cutting force is maximal.



a. Cutting force under the interactive effects of blade type and cutting speed

b. Cutting force under the interactive effects of blade type and cutting mode

c. Cutting force under the interactive effects of cutting speed and cutting mode

Figure 10 Cutting forces under different conditions

The variance analysis of the orthogonal results is shown in Table 1, it can be concluded that three factors of F-value are F_A = 21.316, F_B = 49.141, F_C = 0.222, respectively. The results of variance analysis show that when F-value is greater, the corresponding test factor influences the result of significant effect. Therefore, the blade type on cutting force is the most significant, and the effect of cutting mode is next, the cutting speed is not significant on cutting force. .

Table 1 Test results of analysis of variance table

Sources of variance	SS	df	MS	F
Cutting way (A)	0.143	2	0.072	21.316
Blade type (B)	0.331	2	0.165	49.141
Cutting speed (C)	0.001	2	0.001	0.222
Error	0.007	2	0.003	
Total	3.190	9		

Combined with single factor test and orthogonal tests, the optimal cutting scheme finally determined as: the ramp cutting mode, using straight edge blade, considering other factors such as the production efficiency and the vibration to select the cutting speed.

4 Conclusions

1) Moisture contents of different parts of the cucumber cane are significantly different, and the increase trend presents from root to head.

2) The average tensile strengths of cucumber cane in root, middle and head are 7.35 MPa, 6.30 MPa and 4.68 MPa, respectively. The average elastic moduli are 280.58 MPa, 198.81 MPa and 137.22 MPa. The head and root line with the characteristics of brittle materials, while the middle line with the characteristics of plastic

materials.

3) The single factor test shows that the cutting forces reduced with the increase of cutting speed and the decrease of the cross-sectional area.

4) Through the orthogonal test, F-values corresponding to the cutting mode, the blade type and cutting speed are 21.316, 49.141 and 0.222. The best cutting scheme is using the straight edge blade, in ramp cutting mode.

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