Analysis and test of splitting failure in the cutting process of cabbage root

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Abstract: Cabbage harvester is very useful to replace the manual cabbage harvesting in China. The cutter with single-point clamping way can reduce the maximum and the average cutting force effectively, but may increase the splitting failure. In this study, the mechanics model of cabbage root with single-point clamping way in cutting process was established. According to the analysis of mechanics model, when the sheer stress exceeded the sheer strength ($\tau_a>\tau_0$), splitting failure began to occur. Meanwhile, if the maximum normal stress exceeded the tensile strength ($\sigma_{max}>\sigma_0$), the splitting failure would further become riving failure. The positions of splitting failure would almost locate at the cutting depth l equaled to $R+r$ ($l=R+r$). To reduce the splitting failure, single factor and multi-factor cutting tests about the effect of sliding angle, cutting speed and cutting diameter on splitting failure were carried out. The results showed that the splitting failure would reduce with the increase of sliding angle, cutting speed and cutting diameter. Sliding angle, cutting speed, cutting diameter and the interactions of cutting speed with sliding angle and cutting diameter had significant effect on splitting failure level, and the interaction of sliding angle with cutting diameter and the 3 factors' interaction had no effect. To minimize splitting failure levels, the best cutting combination was that: sliding angle 40°, cutting speed 300 mm/min and cutting diameter 35 mm. This research can provide a basis of how to design a cutter for the cabbage harvester including the optimized cutting combination.

Keywords: cabbage, cutting process, splitting failure, mechanics analysis, tests
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1 Introduction

Cabbage is a kind of common-planted vegetable in China with a massive acreage and production. But harvesting mainly depends on manpower which is labor-intensive and inefficient. Farm labor shortage makes developing a cabbage harvesting system become a practical and practicable choice to change this situation. In this project, designing an appropriate cutter is one of the key techniques, which will determine the harvesting quality. Specifically, the first challenge is this cutter should be able to avoid the damage to cabbage root.

Previously, the stalk damage research mainly focused on sugarcane stalk. Kroes et al.[1] established a kinematic model for the dual basecutter used on sugarcane harvester and obtained the maximum permissible velocity rate to avoid damaging uncut stalks. Qu et al.[2] and Liu et al.[3,4] focused on the research of sugarcane material model, and established the empirical formula of unit cutting force and mechanics model for sugarcane stalk. Based on high-speed photography analysis, they also found cutting speed, cutting position and forward velocity had significant effect on stubble damage[5]. Combined with simulation, Lü et al.[6] analyzed the effect of frequency and amplitude applied on broken sugarcane root and obtained the best parameters to

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minimize the biennial sugarcane root breakage rate. Toledo et al.[7] introduced statistical quality control tools to evaluate the cutting quality for sugarcane and improved the cutting quality in sugarcane harvesting. In addition, the damage properties were also studied on miscanthus stems[8], sunflower stalk[9], safflower stalk[10], etc.

Regarding to the research of cabbage, Li et al.[11] analyzed the effect of cutting way, blade type, cutting speed and cutting diameter on cutting forces of cabbage root and obtained the best cutting combination. Xu et al.[12] further designed the cabbage harvester cutter with convex curve, 0.5 mm knife edge thickness and smooth knife edge based on shear characteristic tests, yet without involving the damage. Du et al.[13] demonstrated that cutting the cabbage root with single-point clamping way could reduce the maximum and the average cutting force effectively, but may cause increase in the splitting failure (SF, a kind of damage along the direction of fiber). Taking the single-point clamping way in the cutter design, it makes sense to analyze SF and propose measures to avoid this phenomenon.

The objective of this study is to establish the mechanics model for cutting cabbage root with single-point clamping way and to explain the reasons for the occurrence of SF. Then, by obtaining the best cutting combination based on the single factor and multi-factor cutting tests to reduce SF.

2 Mechanics analysis

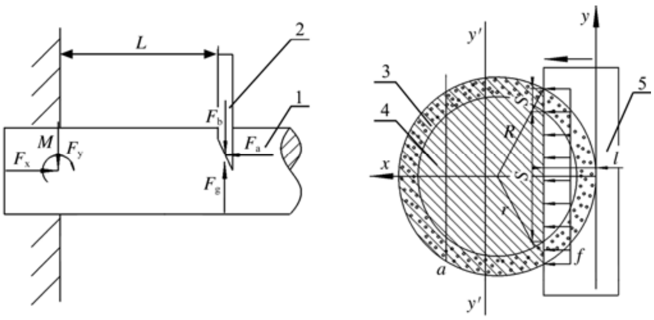
There are two clamping ways for cabbage harvester, one is dual point clamping way, means the ball and the root of the cabbage are clamped by conveyors respectively[14,15]. The other is single-point clamping way, which means only the ball is clamped by conveyors[16,17]. The former has a better cutting quality but the latter needs smaller cutting force and less energy, and is more commonly applied in modern harvesters. So we established the mechanics model for cutting cabbage root with single-point clamping way and analyzed the occurrence of SF.

2.1 Force analysis

The cabbage root with single-point clamping way could be simplified as the model of cantilever showed in Figure 1a. The cutting force by knife could be divided into the horizontal and the vertical. Besides, the clamp impact included the horizontal binding force, the vertical binding force and the torque. So the equilibrium equations of root could be expressed as follows:

$$\begin{cases} F_x - F_a = 0 \\ F_y + F_b - F_g = 0 \\ (F_g - F_b)L - M = 0 \end{cases} \quad (1)$$

where, F_x is the horizontal binding force, N; F_a is the horizontal cutting force, N; F_y is the vertical binding force, N; F_b is the vertical cutting force, N; F_g is the inertia force, N; L is the distance between cutting point and clamping point, mm; M is the binding torque, N·mm.



a. Force analysis of cabbage root b. Force analysis in cross-section

1. Cabbage root 2. Knife 3. Fibrous layer 4. Matrix 5. Knife in cross-section

Note: a-a is the working axis; y′-y′ is the neutral axis; x is the x coordinate; y is the y coordinate.

Figure 1 Force analysis of cutting cabbage root

The dominant force leading to SF in cutting process was the vertical cutting force F_b which could be expressed as follows[3]:

$$F_b = pab \quad (2)$$

where, p is the unit cutting force, MPa; a is the cutting thickness, mm; b is the cutting width, mm.

In the view of cross-section showed in Figure 1b, cabbage root was assumed as a kind of composite with a ring of fibrous layer around the isotropic matrix. The unit cutting force of fibrous layer differed significantly from matrix, so the former was assumed as p_a, the latter p_b. In the cutting process, the cutting thickness a was a constant related to the knife thickness. But the cutting width b, varying with the cutting depth, equaled to the touching length between knife edge and cabbage root.

Therefore, the vertical cutting force F_b could be further expressed as follows:

$$\begin{cases} F_b = 2p_a a(\sqrt{R^2-(R-l)^2}) & 0<l<R-r \\ F_b = 2p_a a(\sqrt{R^2-(R-l)^2}-\sqrt{r^2-(R-l)^2})+ & \\ \quad 2p_b a\sqrt{r^2-(R-l)^2} & R-r\le l\le R+r \\ F_b = 2p_a a(\sqrt{R^2-(l-R)^2}) & R+r<l<2R \end{cases} \tag{3}$$

where, p_a is the unit cutting force of fibrous layer, MPa; p_b is the unit cutting force of matrix, MPa; R is the radius of cross-section, mm; r is the radius of matrix, mm; l is the cutting depth, mm.

The mathematical analysis indicates the Equation (3) is a bimodal curve with two peaks when l equals to $R-r$ and $R+r$. To verify the theory above, the cutting experiment was conducted on the condition that cabbage root in 32 mm diameter position was vertically cut at the speed of 200 mm/min by single-point clamping way. The typically experimental curve of vertical cutting force was displayed in Figure 2. This figure showed there were obviously two peaks as the cutting depth arrived in 6 mm and 28 mm ($l=R-r$, $l=R+r$), which meant the bigger resistance occurred in the cut-in and cut-out areas. The experimental curve revealed the consistency with the equation analysis above. But we can find from experimental curve that the cut-out peak was slightly higher than the cut-in peak, due to the friction which was neglected in theory. As the cutting depth increased, the friction would increase with the expansion of contact areas between knife and cross-section. In general, it also concluded that it was reasonable to regard the cabbage root as a kind of composite.

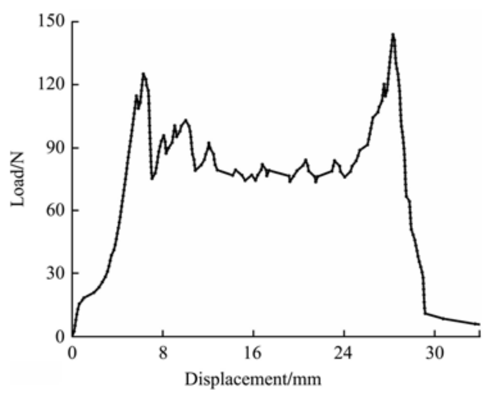


Figure 2 Typically experimental curve of the vertical cutting force

2.2 SF analysis

The sheer force F_s in cutting facet affected by knife edge could be expressed as follows:

$$F_s = F_b - F_g \tag{4}$$

where, F_s is the sheer force, N; The inertia force F_g was a variable related to cutting speed.

Under the hypothesis of that the force in uncut facet affected by sheer force F_s could be separated into an array of uniformly distributed load f, there existed a sheer stress τ in the uncut facet along x direction, which would cause the tendency of SF in uncut vertical facet. According to the Sheer Stress Theorem, sheer stress distribution could be calculated as the equation:

$$\tau_a = \frac{F_s S_{y'}^*}{I_{y'}(S+2s)} \tag{5}$$

where, τ_a is the sheer stress in a-a with a distance of x' from y′−y′, MPa; $S_{y'}^*$ is the static moment on the left areas of a-a towards y′−y′, mm^3; $I_{y'}$ is the inertia moment on the uncut facet towards y′−y′, mm^4; S is the touching length between knife edge and the matrix, mm; s is the touching length between knife edge and the fibrous layer, mm.

According to the Equation (5), τ_a distributed quadratic function in the uncut facet along x direction, and peaked in the neutral axis. If the sheer strength of cabbage root was assumed as τ_0, SF would occur as the sheer stress in a-a exceeded the sheer strength ($\tau_a>\tau_0$).

After SF appeared, it was possible for the damage to become further riving failure, which meant the root would split and rive along the cutting vertical facet. The generation of riving was related not only to sheer stress but also to maximum normal stress. And the normal stress distribution could be calculated with the equation:

$$\sigma_a = \frac{M_l x'}{I_{y'}} \tag{6}$$

where, σ_a is the normal stress in a-a with a distance of x' towards y′−y′, MPa; M_l is the bending moment in the uncut facet, N·mm; x' is the distance between a-a and y′−y′, mm.

According to the Equation (6), σ_a distributed linearly in the uncut facet along x direction. Specifically, the normal stress was 0 in the neutral areas and reached the peak value of σ_{max} when the distance of x' equaled to the maximum. If the tensile strength of cabbage root was assumed as σ_0, after the appearance of SF, the damage would become further riving failure as soon as the maximum normal stress exceeded tensile strength ($\sigma_{max}>\sigma_0$).

Because of the computational complexity and individual diversity, it is difficult to obtain the position of splitting failure (PSF) of cabbage root precisely in theory. Based on numerous cutting experiments, it can be concluded the PSF would almost locate at the position between peak τ_a and σ_a, when cutting depth l equaled to $R+r$(l=$R+r$). This result quite matched the analysis above.

3 Materials and methods

Based on the mechanics analysis above, the main variables affected SF are cutting mode, cutting speed and cutting diameter. Sliding cutting would increase the cutting length and decrease the vertical cutting force and the shear stress, leading to the reduction of SF[18, 19]; cutting speed affected the inertia force by the acceleration. Besides, diameter of cutting facet is also an important variable which affected SF because of different inherent values including the shear strength and the tensile strength. So the 3 factors above and their interactions were taken into consideration in the following cutting tests. The distance between cutting point and clamping point was determined by the cabbage harvester designed previously (L=20 mm).

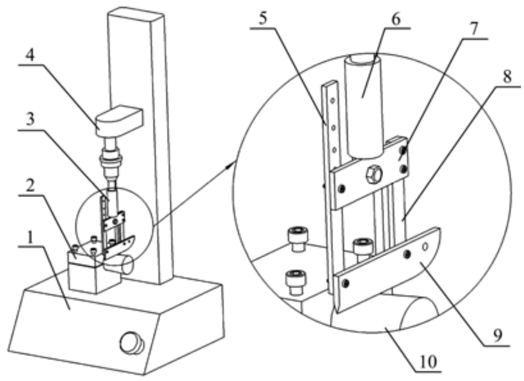
3.1 Materials

The cabbage variety used in the experiments was “Lanzhoubao”, planted in Zhejiang Wuwangnong Seeds Shareholding Co., Ltd. farm, Hangzhou, China. The cabbages were in a certain maturity, then were cut at the junctions of ball-root and root-soil, leaving the middle parts called cabbage root as the experiment materials with a moisture content of 85%-92%[13]. The leaves on the cabbage root were totally removed in order to improve clamping stability. The diameters of samples were among 14-36 mm, and the lengths were among 53-88 mm.

3.2 Cutting test apparatus

The cutting test apparatus was refitted from Instron 5543 materials testing machine (Instron Instrument Trade Co., Ltd., Shanghai, China) which could draw the displacement-load curves. The cutting forces were measured by force sensors with a range of up to 500 N and the cutting speed was measured by displacement sensors with the maximum of 500 mm/min[20].

The cutting test apparatus is shown in Figure 3, the thickness of the knife is 1.4 mm, edge angle is 28°, and material is 65Mn. The designed testing knife carriage was composed of adjustable column, clamping column, beam, supporting column and knife. The sliding angle could be adjusted according to the joint of holes in the adjustable column and the beam. The clamp could fix the cabbage root with single-point clamping way.

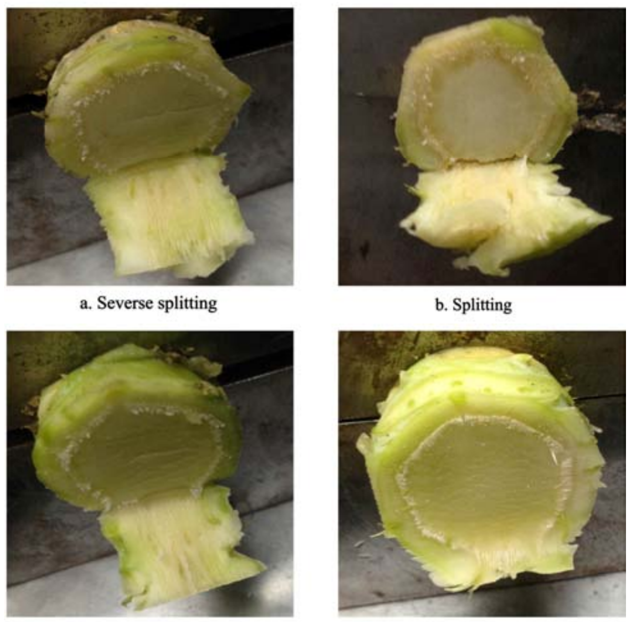


1. Universal testing machine 2. Clamp 3. Knife carriage 4. Sensors 5. Adjustable column 6. Clamping column 7. Beam 8. Supporting column 9. Knife 10. Cabbage root

Figure 3 Schematic diagram of cutting test apparatus

3.3 Methodology

Based on the standard of sugarcane damage tests[4], the splitting failure levels (SFL) were divided into 4 different levels as severe splitting, splitting, slight splitting and none splitting on the basis of splitting thickness showed in Figure 4.



a. Severse splitting b. Splitting

c. Slight splitting d. None splitting

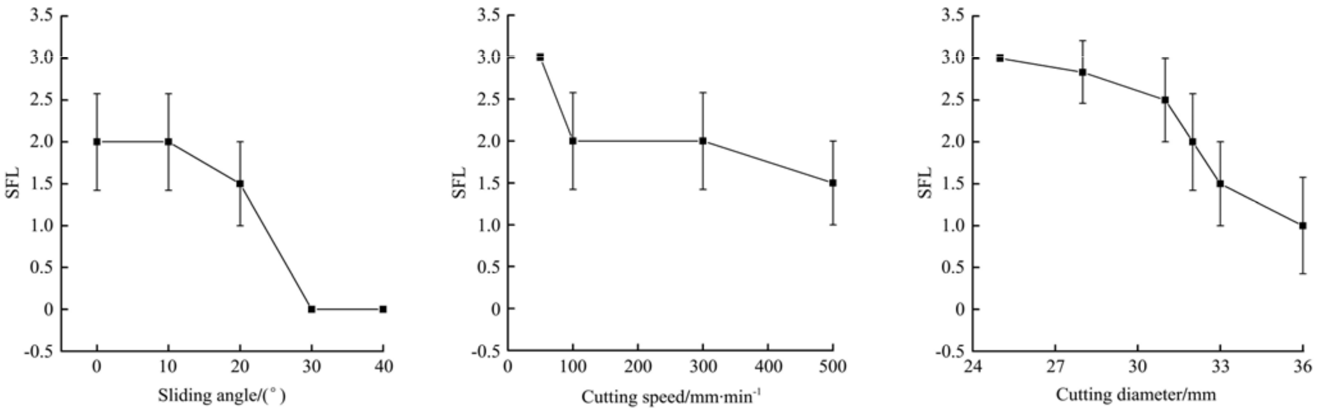
Figure 4 Cabbage root damage classification

Severe splitting was the highest and the splitting facet extended to the clamping point with more than 5 mm splitting thickness. Splitting was better than severe splitting with a splitting thickness ranging between 2-5 mm. Slight splitting only had a shallow track in the splitting facet with less than 2 mm splitting thickness. None splitting was the condition without damage after cutting process. To facilitate statistics and analysis, the 4 SFL were labeled 3, 2, 1, and 0 respectively. Accordingly, the single factor and the multi-factor cutting tests of the 3 factors above were carried out.

4 Results and discussion

4.1 Single factor tests

The factors consisted of sliding angle, cutting speed and cutting diameter in the single factor tests. In the tests of sliding angle, cutting speed and cutting diameter were set as the constants (300 mm/min and 32 mm), the sliding angles were varied as 0°, 10°, 20°, 30° and 40° respectively. Similarly, in the tests of cutting speed, sliding angle and cutting diameter were controlled constantly as 0° and 32 mm, the selected levels were 50, 100, 300 and 500 mm/min, from a low speed to the highest within the range of apparatus. Then the cutting speed and sliding angle were set constantly as 200 mm/min and 0°, the tested levels of cutting diameter were 25, 28, 31, 32, 33 and 36 mm, covering almost the possible cutting position of root. Every test was replicated 6 times and the average values with the standard deviation were shown in Figure 5.



a. Effect of sliding angle b. Effect of cutting speed c. Effect of cutting diameter

Figure 5 Results of single factor tests

Figure 5a presented that SFL decreased with the increase of sliding angle, and less of SF might occur when the sliding angle increased to 30°. This was mainly because when the root was cut in the sliding way, the numerous micro-teeth in the knife edge would play an important role in cutting the fiber by rubbing in a tilt angle. Meanwhile, the actual wedge angle cutting into the root decreased with the sliding angle increased. The increase of rubbing action and the decrease of wedge angle would probably cause the reduction of vertical cutting force, which had been proved by Igathinathane in the corn stalk cutting experiment[21]. According to the mechanics analysis above, reduction of vertical cutting force would further reduce SF. Besides, 30°-50° was also recommended as the most appropriate sliding angle to cut materials[19], explaining the sharp drop when the sliding angle increased to 30°. Figure 5b showed that SFL also decreased with the increase of cutting speed, but there was no significant difference when the speed ranged from 100 mm/min to 500 mm/min. This is because cutting speed is a variable related to the inertia force as mentioned above. In the cutting process, the collision between the knife and the root might generate an inertia force contrary to the vertical cutting force, regarding cutting speed as the initial speed to this collision. Moreover, the higher initial speed would cause the bigger inertia force by the acceleration. Inferred from the mechanics analysis above, SF would finally decrease with the cutting speed increasing. However, because of the small-range speed limited by the cutting test apparatus, the cutting speed did not present a significant effect on SFL, compared with the results of obvious cutting force change in large-range cutting speed[22]. Figure 5c showed that SFL decreased with the cutting diameter increasing, especially dropped significantly when the diameter exceeded 30 mm. This is because the main chemical content in different cutting diameter is distinguishing. Specifically, the main composition resistant to cutting, the crude fiber content declined with the diameter increasing and got the lowest when diameters ranged from 30 mm to 35 mm[13]. Technically, the smaller the diameter, the higher the lignification of the root, contributing to improving tensile strength[23]. So it made sense that SF was more likely to occur under the smaller diameter .

4.2 Multi-factor tests

According to the single factor tests above, SF was definitely associated with sliding angle, cutting speed and cutting diameter. To further verify the factors' significance and influence, we took the 3 factors above into consideration as well as their interactions to conduct the cutting tests. The multi-factor tests used a method called factorial design. On principle, the selected three levels of sliding angle were 20°, 30° and 40°, which were among the recommended ranges previously. Similarly, 200, 300 and 400 mm/min were selected as the levels of cutting speed and diameters of 28, 32 and 35 mm were selected as the cutting diameter levels. All of the levels above were representative based on the results of single factor tests. So there were 27 group tests completely, and each group was replicated 6 times and the averages were showed in Table 1.

Variance analysis and mean comparison were applied to analyze the factors' significance and influence on SFL. The results were displayed in Table 2, showing that sliding angle, cutting diameter and the interactions of cutting speed with sliding angle and cutting diameter had a highly significance (p<0.01), and cutting speed was significant (p<0.05), but the interaction of sliding angle with cutting diameter and the 3 factors' interaction had no effect on SFL. The mean comparison revealed that the SFL decreased when the sliding angle increased, especially declined sharply when the sliding angle increased to 30°. In the comparison of cutting speed, 300 mm/min was the optimal parameter with the minimal SFL among the selected levels, but had no significant advantage. And the SFL decreased as the cutting diameter increased, but there was little difference between the diameter of 32 and 35 mm. We found the mean comparison results analyzed above were mainly in accord with the single factor tests. Based on minimizing SFL principle, the best cutting combination was A3B2C3: sliding angle 40°, cutting speed 300 mm/min and cutting diameter 35 mm, which was accordingly the 24th test in Table 1. However, we can see the results of tests 14th, 15th, 17th, 18th, 19th, 20th, 21st, 23rd, 26th and 27th were also acceptable with relatively low mean values of SFL compared to 24th test. That means it is flexible to choose one of the appropriate tests above as the best cutting combination on practical application condition.

Table 1 Results of multi-factor tests

Test numbers	Factors			Mean values of SFL
	A	B	C	
1	1(20)	1(200)	1(28)	2.50
2	1(20)	1(200)	2(32)	2.33
3	1(20)	1(200)	3(35)	1.67
4	1(20)	2(300)	1(28)	2.17
5	1(20)	2(300)	2(32)	1.67
6	1(20)	2(300)	3(35)	1.33
7	1(20)	3(400)	1(28)	2.33
8	1(20)	3(400)	2(32)	1.50
9	1(20)	3(400)	3(35)	1.33
10	2(30)	1(200)	1(28)	1.50
11	2(30)	1(200)	2(32)	1.33
12	2(30)	1(200)	3(35)	0.83
13	2(30)	2(300)	1(28)	0.83
14	2(30)	2(300)	2(32)	0.17
15	2(30)	2(300)	3(35)	0.17
16	2(30)	3(400)	1(28)	1.83
17	2(30)	3(400)	2(32)	0.17
18	2(30)	3(400)	3(35)	0
19	3(40)	1(200)	1(28)	0.17
20	3(40)	1(200)	2(32)	0.17
21	3(40)	1(200)	3(35)	0
22	3(40)	2(300)	1(28)	0.83
23	3(40)	2(300)	2(32)	0.17
24	3(40)	2(300)	3(35)	0.33
25	3(40)	3(400)	1(28)	1.83
26	3(40)	3(400)	2(32)	0.17
27	3(40)	3(400)	3(35)	0

Table 2 Results of variance analysis and mean comparison

		Factors			Interactions			
		A	B	C	A*B	A*C	B*C	A*B*C
F-value		163.49	6.96	65.51	11.67	1.14	11.76	1.40
p-value		<0.0001	0.0013	<0.0001	<0.0001	0.3415	<0.0001	0.2010
Mean	1	1.870	1.167	1.554				
	2	0.759	0.852	0.853				
	3	0.408	1.018	0.629				

In the next stage of designing cutter for cabbage harvester with single-point clamping way, the best combination above can be recommended as a reference to reduce SF. While associating with practical application, the cutting diameter of 35 mm is too close to the ball, which may damage the ball and remove excess leaves. In fact, diameter of 32 mm is located on the position of 10 mm to 15 mm above the bottom leaf, which would be more suitable for cutting and separating the redundant leaves. In addition, it is better enough to take the sliding angle of 30° and the cutting speed of 300 mm/min as the cutting parameters in terms of energy saving. As a consequence, the 14th cutting combination in the multi-factor tests will be more practical as the working parameters in the harvester cutter design.

5 Conclusions

1) The mechanics model analysis proved the vertical cutting force had two peaks when $l=R-r$ and $l=R+r$. When the sheer stress exceeded sheer strength ($\tau_a>\tau_0$), SF occurred. Meanwhile, the maximum normal stress exceeded tensile strength ($\sigma_{max}>\sigma_0$), the SF would become further riving failure. The PSF would almost locate at the cutting depth l equaled to $R+r$ ($l=R+r$).

2) The single factor tests showed that SFL decreased with the increasing of sliding angle, cutting speed and cutting diameter respectively. Less of SF occurred when the sliding angle exceeded 30° or the cutting diameter exceeded 30 mm. There was no significant difference when the speed ranged from 100 mm/min to 500 mm/min.

3) The multi-factor tests demonstrated that sliding angle, cutting speed, cutting diameter and the interactions of cutting speed with sliding angle and cutting diameter had significant effect on SFL, and the interaction of sliding angle with cutting diameter and the 3 factors' interaction had no effect on SFL. To reduce SF, the best cutting combination was that: sliding angle 40°, cutting speed 300 mm/min and cutting diameter 35 mm.

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[References]

[1] Kroes K, Harris H D. A kinematic model of the dual basecutter of a sugar cane harvester. Journal of Agricultural Engineering Research, 1995; 62(3): 163－172.

[2] Qu Y G, Wegner M, Yang D T, Liu Q T, Zheng D K, Wang M M, et al. Mechanization technology: The key to sugarcane production in China. Int J Agric & Biol Eng, 2013; 6(1): 1–27.

[3] Liu Q T, Qu Y G, Qing S L, Wang W Z. Cutting force calculation of sugarcane stalk. Transactions of the CSAM, 2006; 37(9): 89–92. (in Chinese with English abstract)

[4] Liu Q T, Qu Y G, Qing S L, Wang W Z. Mechanics analysis on stubble damage of sugarcane stalk during cutting by smooth-edge blade. Transactions of the CSAM, 2007; 38(9): 51–54. (in Chinese with English abstract)

[5] Liu Q T, Qu Y G, Qing S L, Huang S X. High-speed photography analysis on the damage process in cutting sugarcane stalk with smooth-edge blade. Transactions of the CSAM, 2007; 38(10): 31–35. (in Chinese with English abstract)

[6] Lü Y, Yang J, Liang Z X, Mo J L, Qiao Y H. Simulative kinematics analysis on the affecting factors of rate of broken biennial root of single base cutter of sugarcane harvester. Transactions of the CSAM, 2008; 39(4): 50–55. (in Chinese with English abstract)

[7] Toledo A, Silva R P, Furlani C E A. Quality of cut and basecutter blade configuration for the mechanized harvest of green sugarcane. Scientia Agricola, 2013; 70(6): 384–389.

[8] Liu Q, Mathanker S K, Zhang Q, Hansen A C. Biomechanical properties of miscanthus stems. Transactions of the ASABE, 2012; 55(4): 1125–1131.

[9] Ince A, Ugurluay S , Guzel E, Ozcan M T. Bending and shearing characteristics of sunflower stalk residue. Biosystems Engineering, 2005; 92(2): 175–181.

[10] Oezbek O, Seflek A Y, Carman K. Some mechanical

properties of safflower stalk. Applied Engineering in Agriculture, 2009; 25(4): 619–625.

[11] Li X Q, Wang F, Guo W J, Gong Z L, Zhang J. Influencing factor analysis of cabbage root cutting force based on orthogonal test. Transactions of the CSAE, 2013; 29(10): 42–48. (in Chinese with English abstract)

[12] Xu L M, Yao H L. Research on shear characteristics of Chinese cabbage rootstalk. Agricultural Mechanization in Asia, Africa and Latin America, 2009; 40(3): 30–34.

[13] Du D D, Wang J, Qiu S S. Optimization of cutting position and mode for cabbage harvesting. Transaction of the CSAE, 2014; 30(12): 34–40. (in Chinese with English abstract)

[14] Hachiya M, Amano T, Yamagata M, Makota K. Development and utilization of a new mechanized cabbage harvesting system for large fields. Japan Agricultural Research Quarterly, 2004; 38(2): 97–103.

[15] Wang J, Du D D. Cabbage harvester and its methodology: China, 201310248988.9, 2013-06-27. (in Chinese)

[16] Hansen C J. Harvesting machine for cabbage, or the like: US, 3827503, 1974-08-06.

[17] Wang J, Hu J B. A post transporting working system for cabbage harvester: China, CN201310188727.2, 2013-08-21.

[18] Osman A N, Li X, Zhang D X. Effects of tilt angle of disk plough on some soil physical properties, work rate and wheel slippage under light clay soil. Int J Agric & Biol Eng, 2011; 4(2): 29–35.

[19] 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.

[20] Wang J W, Tao G X, Liu L J, Pan Z W, Zhang C F. Field experimental study on pullout forces of rice seedlings and barnyard grasses for mechanical weed control in paddy field. Int J Agric & Biol Eng, 2014; 7(6): 1–7.

[21] Igathinathane C, Womac A R, Sokhansanj S. Corn stalk orientation effect on mechanical cutting. Biosystems Engineering, 2010; 107(2): 97–106.

[22] Wu M L, Guan C Y, Tang C Z, Chen S Y, Luo H F, Xie F P. Experiments on influencing factors of cutting force of rape stem. Transaction of the CSAE, 2009; 25(6): 141–144.

[23] Genet M, Stokes A, Salin F, Mickovski S B, Fourcaud T, Dumail J F, Beek R. The influence of cellulose content on tensile strength in tree roots. Plant and Soil, 2005; 278(1-2): 1–9.