DEVELOPMENT AND TEST OF CORN STRAW KNEADING AND CONVEYING DEVICE / 玉米秸秆揉切输送装置的研制与试验

Geng Aijun[1,2], Gao Ang[1)], Zhang Yinuo[1)], Zhang Ji*[1)], Zhang Zhilong[1)], Hu Xiaolong[1)]
[1)] Shandong Agricultural University, College of Mechanical and Electrical Engineering/ China;
[2)] Shandong Provincial Engineering Laboratory of Agricultural Equipment Intelligence/ China
Tel: +86-0538-8242500; E-mail: sdauzhangji@163.com
DOI: https://doi.org/10.35633/inmateh-65-03

***Keywords:** Straw utilization; Crushing straw; Kneading and cutting straw Test;*

ABSTRACT
Aiming at the low comprehensive utilization rate of corn straw resources, a straw kneading and cutting conveyor suitable for corn harvester was designed to improve the utilization rate of corn straw resources. The workbench module of ANSYS is used to carry out modal analysis of the two blades, and it is determined that the vibration frequency will not cause damage to the blade sweeping bore. By changing the structure of the movable blade shaft, the speed of the blade shaft can be reduced while ensuring the effect of straw crushing and collecting. In order to determine the best working parameters, three-factor and three-level orthogonal test was carried out with blade arrangement, blade shaft speed and length of feed straw as test factors, and the crushing rate of straw as evaluation index. The results show that the main factors influencing the crushing rate of straw are blade shaft speed, blade arrangement and the minor factor is the length of feed straw. Finally, the optimum combination parameters, blade arrangement, blade shaft speed 400 r/min and whole plant feed with straw, were determined. The corresponding straw crushing rate was 96.39%. The research meets the requirements of straw crushing and can provide technical scheme for comprehensive utilization of corn straw.

摘要
针对玉米秸秆资源的综合利用率低的问题，设计了一种适用玉米收获机的秸秆揉切输送装置以提高玉米秸秆资源的利用率。利用 ANSYS 的 workbench 模块对两种刀片进行模态分析，确定振动频率不会导致刀片扫膛受损；通过改变动刀轴的结构在保证秸秆粉碎及收集效果的同时降低刀轴转速以减少能耗。为确定最佳工作参数，以刀片排列方式、刀轴转速及喂入秸秆长度为试验因素，以秸秆粉碎率为评价性指标，进行三因素三水平正交试验，结果表明影响秸秆粉碎率的主要因素为：刀轴转速、刀片排列方式，次要因素为喂入秸秆长度。最终确定最优组合参数刀片为混合排列、刀轴转速 400r/min、喂入秸秆为整株，对应试验的秸秆粉碎率为 96.39%。该研究满足秸秆粉碎要求可为玉米秸秆综合利用提供技术方案。

INTRODUCTION

China is a big agricultural country (*Du Y. et al., 2019, Liu C. et al., 2019*), and corn is grown in a large area (*Ding N. et al., 2021*). Corn stalks are rich in nutrients, which can be used as animal feed or they can be returned to the field as plant nutrients (*Liu C. et al., 2017*). Although the method of returning whole corn stalks to the field avoids the waste of resources and environmental pollution, the large amount of returning to the field leads to the slow decomposing efficiency of the stalks, and a large amount of accumulation on the surface of the land affects the growth of next season crops (*Shi N. et al., 2020*). The results showed that the effect was the best when the amount of straw returned to the field is 30-50% (*Zhao H. et al., 2003*). The lower part of corn straw 60 cm accounted for one third of the weight of straw, so the lower part of corn straw is crushed and returned to the field, and the upper part of corn straw is crushed and collected to maximize the utilization of straw resources.

Researchers had conducted many studies on the cutting characteristics of crops and straw crushing devices (*Wang l. et al., 2020, He J. et al., 2018, Shi Y. et al., 2019*). The existing corn harvesters chop straw mainly in the drum type, the scalpel cutting type and the stalk cutting type (Zhang J. et al., 2018). Drum-type is cut by multiple moving knives and fixed knives, but the cut straw is cylindrical, which is not palatable to animals. The stalk is unsupported when cutting with a flail knife, and cutting the stalk requires a faster rotation speed and consumes more power. The stem-drawing knife extrusion-cutting type is composed of two stem-drawing rollers with opposite rotation directions. The two stem-drawing rollers must meet the same speed and the blades are on the same horizontal line, otherwise it is easy to collide (*Xin S. et al., 2020*).

Aiming at the problems of these three straw cutting methods, this paper designs a straw kneading and conveying device installed below the stem pulling roller device. The blades of the serrated blade and the triangular blade and the serrated blade are matched with the fixed knife to shred the straw. At the same time, the stalks are conveyed in a spiral arrangement by the cutting blades, which improves the palatability of the stalk feed for animals, reduces the speed of the knife shaft, and reduces the power demand.

MATERIALS AND METHODS

Structure and working mechanism

In the corn harvester table shown in Figure 1, the straw kneading and cutting conveyor was installed under the puller roll. During the corn harvest, corn straw was fed to the heading roll under the push and pull of the conveying chain. At the same time, the rotor milling cutter under the heading roll cuts off the straw and sends the lower part of the cut straw into the straw kneading and cutting conveyor. The straw was harvested under the pulling action of the heading roll, and the remaining corn straw was fed into the straw kneading and cutting conveyor. Under the action of moving blade and fixed blade in the straw kneading and cutting conveyor, the straw was crushed, and then centralized transported to the fan to complete the straw collection.

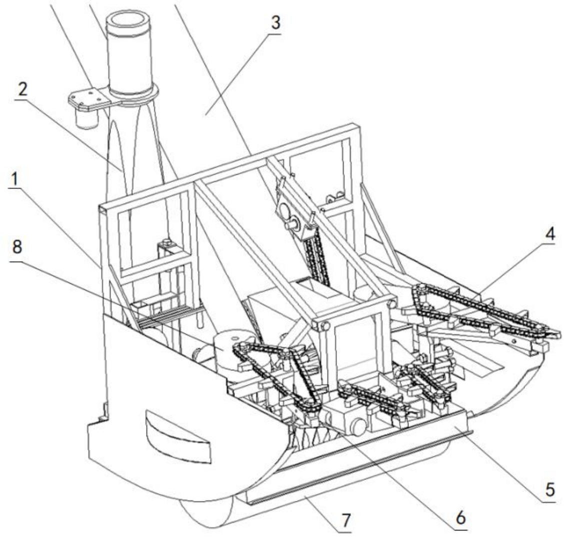

Fig. 1 - Corn harvester cutting table

1. Rack; 2. Draught fan; 3. Ear conveying device; 4. Conveying chain; 5. Rotor milling cutter; 6. Shapping roll; 7. Straw kneading and cutting conveying device

In order to verify the practicability of straw kneading and conveying device, designing the testbed of straw kneading and conveying device has been done. It was made of bottom case, rack, cutter shaft, shaft sleeve, triangular blade, jagged blade, adjustable-speed motor, drive system and so on. It is shown in fig. 2.

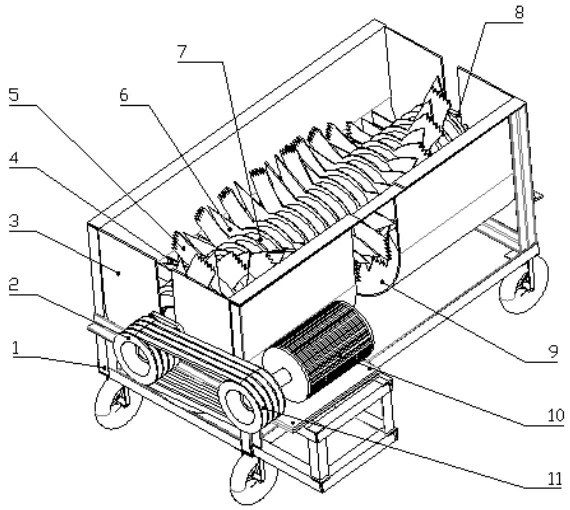

Fig.2 - Structure diagram of straw cutter

1. Rack; 2. Belt pulley; 3. Type a Belt pulley; 4. The fixed blade; 5. Triangular blade; 6. Jagged blade; 7. Type a Shaft sleeve; 8. Cutter shaft; 9. The outlet of straw delivery; 10. Motor; 11. Transmission

The straw kneading and conveying device was installed under the pull stem device of corn harvester. After the corn straw in the field was cut by the stubble cutter harvester, corn bundles were picked by pulling of double-roller stem pulling device and the straw was transported insider straw kneading and conveying device. The straw was cut with the blade of cutter shaft and the stationary knife of the bottom case. The cutting edges of the blade are arranged spirally on the tool shaft, which produce transverse thrust on the straw during the work, and transport the straw to the straw conveyor port on the bottom shell while crushing the straw.

The design of cutter shaft

While cutting the straw, the movable blade also leaves a space in the bottom shell of the straw kneading and cutting conveyor device to transport the chopped straw, and the saw tooth has a good effect of kneading and cutting the straw (*Zhang Z. et al., 2021*). The movable blade was designed as a serrated blade with a multiple serrations on the outer circumference as shown in Figure 3. In order to avoid the blockage of corn straw caused by too small space reserved by serrated blade in the bottom shell of the device, a triangular blade with a serrated blade on the outer circumference was designed, as shown in Figure 4. As the sawtooth blade has a good kneading and cutting effect on corn straw, the triangular blade is helpful for the conveying efficiency of corn straw in the bottom shell of the device and prevents blockage. Therefore, the blades on the cutter shaft are arranged in the way of sawtooth blade and triangular blade spacing, and the cutting blades are arranged in a spiral shape, as shown in Figure 5.

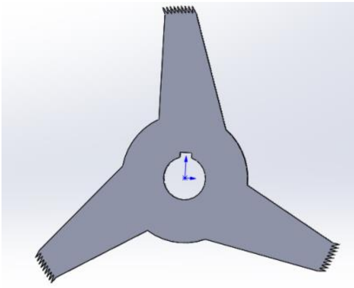

Fig. 3 - Jagged blade

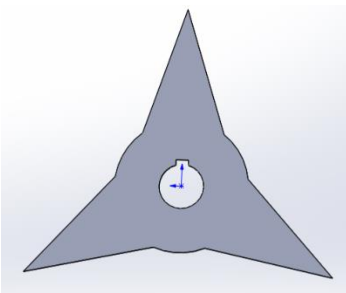

Fig. 4 - Triangular blade

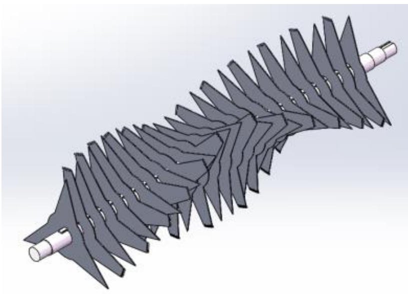

Fig. 5 - Knife shaft

The corn straw contains about 40% fibrin (*Chen Z. et al., 2013*), which had great influence on the mechanical strength and elasticity of straw. Cutting the straw with the measures of smooth cut could effectively destroy fibrin physical property of straw (*Mou X. et al., 2020*). The sliding cutting angle and cutting corners had great effect on cutting energy consumption when cutting, so selecting reasonable cutting angle could decrease power loss effectively and increase straw smashing quality (*Liu P et al., 2019*). Figure 6 shows the force when the movable blade and the fixed blade clamp the straw.

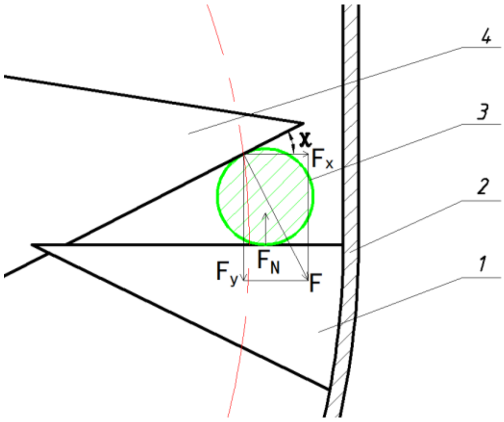

Fig. 6 - Stress analysis

1. Fixed blade; 2. Bottom shell; 3. Straw; 4. Movable blades

The moving blade exerts a shearing force F on the straw during high-speed rotation, which could be decomposed into a force F_X in the direction of leaving the clamping range of the movable knife and the fixed knife and a vertical downward pressure F_y. The fixed knife provides a vertical upward force for the straw. The supporting force F_N, the condition that the material was not pushed out was $\chi \leq \emptyset_1 + \emptyset_2$, where χ was the sliding angle of the movable knife, ϕ_1 was the friction angle of the movable knife to the straw, and ϕ_2 was the friction angle of the fixed knife to the straw. χ changes during the cutting process, so it was required that the maximum value of the pushing angle should meet the conditions of the above formula. Usually, ϕ_1=32°, ϕ_2=18°, so χ was generally less than 50°. When the sliding cut angle was in the range of 35-45°, the average cutting torque was lower and the cutting energy consumption was lower. In order to cut reliably, the sliding cut angle χ=30° was used.

Design of cutter shaft

The long section of straw that was not cut when the straw was cut was easily entangled in the gap between the main shaft and the blade, which affected the normal operation of the cutter shaft. The shaft sleeve with an outer diameter of 150 was designed to be installed between adjacent blades on the cutter shaft. On the one hand, the shaft sleeve can be used to axially space and position the blades. On the other hand, the larger outer diameter can prevent the cutter shaft from tangling grass.

The distance between adjacent blades was 44 mm. That was to say, the width of the sleeve was 44 mm. The fixed blades were installed in the middle of two adjacent blades in a staggered way. A keyway was provided on the cutter shaft and the blade, and the key was matched to realize the cutter shaft to drive the blade to rotate at a high speed. In order to make the cutting edges of the blades spirally arranged, the opening positions of the key grooves on the blades are also different, and the angle between the key grooves of two adjacent blades is about 7°. It was assembled on the cutter shaft according to the principle of one sleeve and one blade. The cutter shaft was installed on the shell through two bearings, and finally connected to the speed regulating motor through the belt drive system.

Experiment design

The main working part of the straw kneading and cutting conveying device was the blade. The blade structure and rotating speed directly affect the degree of straw crushing. For the ear picking device, when the ordinary ear picking roller was used, the straw fed into the straw kneading and cutting conveying device was the whole straw, while when the stalk pulling knife roller was used as the ear picking device, the straw fed into the straw kneading and cutting conveying device was pre-cut to 7 cm or 14 cm. In order to obtain the best smashing effect, the three variable factors of the blade arrangement, the rotation speed of the knife shaft and corn stalk length of the feed straw were tested to determine the optimal combination.

Test equipment and materials

The test bench of the straw kneading and cutting conveying device was shown in Figure 7. The motor selection model was YVP132M-4 variable frequency speed regulating three-phase asynchronous motor, with a power of 7.5KW and a torque of 49.7Nm. Choose Senlan SB4037.5 frequency converter to control the motor speed.

Fig. 7 - Test bench

In the experiment, corn stalks were selected as field stalks harvested after maturity of corn. The stalks were straight, free from diseases and insect pests, and suffered no bending. The stalks above 60 cm on the ground were cut and collected, as shown in Figure 8.

Fig. 8 - Corn stover

According to the requirements of "NYT 2088-2011 corn silage harvester operation quality" standard (Lv J. et al., 2016), corn straw silage should be carried out under the condition of 65% - 70% moisture content of straw. The qualified cutting length of silage corn straw was 3cm-5cm, and the required crushing qualified rate was greater than or equal to 95%. In this paper, the qualified length of straw crushing was selected to be 5cm, and the crushed total straw and the weight of the qualified length of straw were weighed by electronic scale, as shown in Figure 9. The qualified rate of crushing was calculated as follows:

$$\mathrm{p} = \frac{ma}{\mathrm{m}} \times 100\% \tag{1}$$

where， p - qualified rate of straw crushing, %；

ma - mass of straw with qualified crushing length, kg；

m - total mass of crushed straw, kg.

Fig. 9 - Weighing the straw

RESULTS

Stress analysis

Modal analysis (*Zahid, F.B. et al., 2020*) was used to calculate the natural frequency and vibration mode of the structure (*Bo H. et al., 2016*). The blade rotates under the action of the blade shaft, resulting in vibration deformation. It was necessary to avoid the natural frequency of the structure when designing to prevent the blade from sweeping bore and parts from being damaged due to excessive vibration. Modal analysis of the two blades was carried out in this paper.

Import the three-dimensional models of the two blades established by SolidWorks into the Ansys workbench module, create the analysis type as "Modal", set the material of the blade to high-strength 65 manganese steel, density ρ=7.85g/cm^3, Young's modulus E=196500~198600MPa, Poisson's ratio μ=0.288. After loading the model, the sixth-order mode was analysed and calculated, and the resulting sixth-order modal shape diagrams were shown in Figures 10 and 11. It could be seen that the maximum deformation of the serrated blade was 0.02268mm, and the maximum deformation of the triangular blade was 0.03422mm. The deformation of the blade was small, and vibration deformation will not cause problems such as blade sweeping and damage to parts.

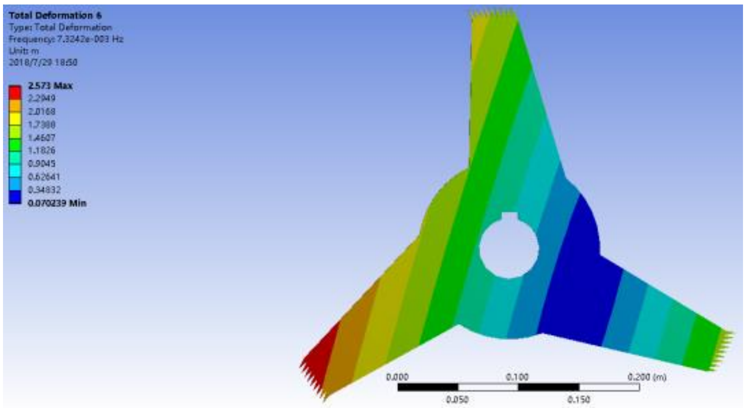

Fig. 10 - Six-order modal shape of jagged blade

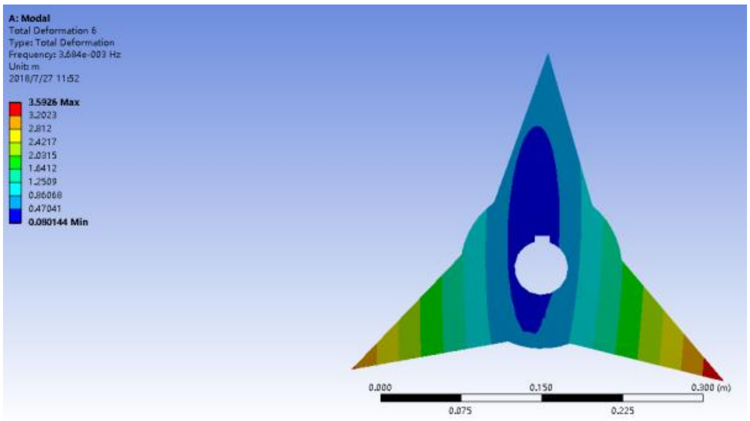

Fig. 11 - Six-order modal shape of triangular blade

Analysis of test data

In order to determine the factor level of the rotation speed of the cutter shaft, a single factor test was performed on the test bench first, and a mixed arrangement of blades was selected. The rotation speed directly affects the power loss. In order to reduce the power loss of the device, determine the minimum rotation speed that meets the shredding needs, select the rotation speed to start the test from 200r/min, and gradually increase the rotation speed. Calculated from the test data, the average pass rate of straw crushing was 65.28% when the rotating speed was 200r/min. The higher the rotating speed, the higher the pass rate of crushing. When the rotating speed was 350r/min, the average pass rate of straw crushing could reach 92.53%. The three levels of cutter shaft speed were 300r/min, 350r/min, and 400r/min.

The blade arrangement and straw feeding length were tested under these three speeds, and the data were shown in figure 12. In the figure, the broken line connected by diamond represents the arrangement of mixed blades, the broken line connected by square represents serrated blades, and the broken line connected by triangle represents triangular blades.

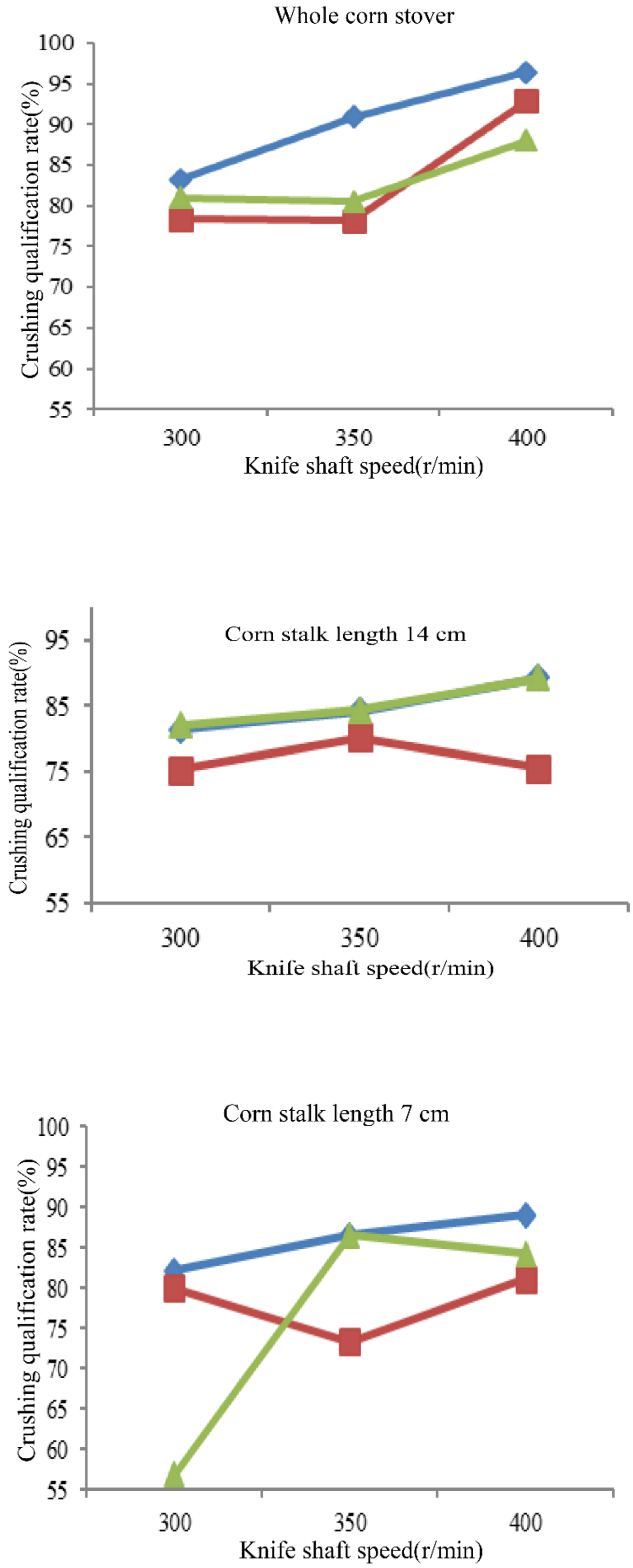

Fig.12 - Effect of different combination of factors on the grinding yield

In order to improve the qualified rate of straw crushing, three factors and three levels of orthogonal test were carried out on three variable factors: blade arrangement (A), blade shaft speed (B) and feed straw length (C). The factors and levels are shown in Table 1. The test results are shown in Table 2.

Table 1

Experimental factors and levels

Levels	Factors		
	Blade arrangement (A)	Blade shaft speed (B) (r/min)	Corn stalk length (C) (cm)
1	Mixed arrangement	300	7
2	Zigzag arrangement	350	14
3	Triangular arrangement	400	Whole corn stover

Table 2

Test plan and test data

Serial number	A	B	C	Average accuracy /%
1	1	1	1	82.19
2	1	2	2	84.21
3	1	3	3	96.39
4	2	1	2	80.19
5	2	2	3	78.18
6	2	3	1	81.19
7	3	1	3	80.96
8	3	2	1	86.52
9	3	3	2	89.24

Analysis of variance

The test results were imported into SPSS for variance analysis (*Tanner-Smith, E.E., 2014, Guo M. et al., 2017*). The results were shown in Table 3. The Sig values were all greater than 0.05, which indicated that there was no significant difference in average yield due to different levels of factors. Factor A and factor B have a significant influence on the test results, of which factor B has a greater influence on the test results, while factor C has no influence on the significance of the test results. At this time, you can select the combination of A1, B3, and C3 with the largest average number from Figure 10 to form the optimal combination of A1B3C3. The resulting optimal combination plan A1B3C3 exists in the orthogonal test table 2. Therefore, the combination of A1B3C3 was the best. The optimal combination plan was that the blades are arranged in a mixed manner, the speed of the knife shaft was 400 r/min, and the straw was fed to the whole plant.

Table 3

Variance analysis table

Source of variation	Sum of squares	Degree of freedom	Mean square	F	Sig.
A	96.771	2	48.386	1.842	0.352
B	100.345	2	50.172	1.910	0.344
C	5.473	2	2.736	0.104	0.906
Error	52.53	9	/	/	/

CONCLUSIONS

A straw kneading, cutting and conveying device installed under the rod puller was designed. The stalk was shredded by the blades of the serrated blade, the triangular blade and the serrated blades and the fixed knife. At the same time, the stalks were conveyed in a concentrated manner by the spiral arrangement of the cutting blades. While ensuring the effect of straw crushing and collecting, the rotation speed of the cutter shaft was reduced, and the power consumption was reduced.

The cutting angle of the cutting edge was calculated by analysing the cutting process, and a modal analysis of the blade was made. The blade vibration and deformation are small, which avoids problems such as blade sweep.

The influencing factors of the crushing pass rate of straw were tested by design test. Variance analysis showed that when the blades were mixed and arranged, the rotation speed of the cutter shaft was 400r/min, and the feed straw was the whole plant, the highest pass rate of straw crushing was 96.39%, which was the best combination scheme.

ACKNOWLEDGEMENT

This work was sponsored by the Shandong Provincial Key Science and Technology Innovation Engineering Project (2018CXGC0217) and China Post-Doctoral Fund Project (2017M612309).

REFERENCES

[1] Bo, H., Lin, J. (2019). Study on the design and parameters of corn straw returning machine (玉米秸秆还田机的设计与参数研究). *Journal of Agricultural Mechanization Research*, Vol.11, pp.99-103, Beijing/China.

[2] Ding, N., Li H., Yan, A., Li, S., Han, L., Wei W. (2021). Experiment on Multi-stage Continuous Cold Roll Forming of Straw (秸秆多级连续冷辊压成型试验研究). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.52, issue 5, pp.279-285, Beijing/China.

[3] Du, Y., Fu, S., Mao, E., Zhu, Z., Li, Z. (2019). Development Situation and Prospects of Intelligent Design for Agricultural Machinery(农业机械智能化设计技术发展现状与展望). *Transactions of the Chinese Society for Agricultural Machinery,* Vol.50, issue 9, pp.1-17, Beijing/China.

[4] Guo, M., Feng, B., Guan, Y. (2017). Experimental Design and Software Application (实验设计与软件应用). *Beijing: Chemical Industry Press, 7*.

[5] He, J., Li, H., Chen, H., Lu, C., Wang, Q. (2018), Research Progress of Conservation Tillage Technology and Machine (保护性耕作技术与机具研究进展). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.49, issue 4, pp.1-9, Beijing/China.

[6] Liu, C. (2017). Vigorously promote the mechanized return of corn stalks to the field (大力推进玉米秸秆机械化还田技术). *Use and Maintenance of Agricultural Machinery*, Vol.10, pp.68-73, Harbin/China.

[7] Liu, P., He, J., Li, H., Wang, Q., Lu, C., Lou, S., Liu, W., Cheng, X. (2019), Kinematic analysis and experiment of corn spreading process. *INMATEH-Agricultural Engineering*, Vol.58, issue 2, pp.83-95, Beijing/China.

[8] Liu, C., Lin, H., Li, Y., Gong, L., Miao, Z. (2019). Analysis on Status and Development Trend of Intelligent Control Technology for Agricultural Equipment(农业装备智能控制技术研究现状与发展趋势分析). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.51, issue 1, pp.1-18, Shanghai/China.

[9] Lv Ji., Yang Y., Shang Q., Wang, Y., Li, Z., Tong, S., Zhu, Q. (2016). Experimental study on shredding performance of corn silage harvester (玉米青贮收获机切碎性能试验研究). *Journal of Northeast Agricultural University*, Vol.47, issue 4, pp.102-108, Harbin/China.

[10] Mou, X., Jiang, H., Sun, Y., Xu, H., Yao, Y., Geng, D. (2020). Simulation Optimization and Experiment of Disc-type Grain Crushing Device of Silage Corn Harvester (青贮玉米收获机碟盘式籽粒破碎装置仿真优化与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.51, issue s1, pp.218-226, Zibo/China.

[11] Shi, N., Chen, H., Wei, Z., Hou, S., Zou, Z., Wang X. (2020). Design and experiment of stalk returning proportion adjusting device for corn original stubble (玉米原茬地秸秆还田比例调节装置设计与试验). *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, Vol.36, issue 21, pp.11-22, Harbin/China.

[12] Shi, Y., Luo W., Hu Zh., Wu, F., Gu, F., Chen, Y. (2019). Design and Test of Equipment for Straw Crushing with Strip-laying and Seed-belt Classification with Cleaning under Full Straw Mulching(全量秸秆粉碎条铺与种带分型清秸装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.50, issue 4, pp58-67, Nanjing/China.

[13] Tanner-Smith, E.E., Tipton, E. (2014). Robust variance estimation with dependent effect sizes: practical considerations including a software tutorial in Stata and SPSS. *Research Synthesis Methods*, Vol.5, issue 1, pp.13-30, Nashville/USA.

[14] Wang, L., Zhang, Z., Liu, T., Wang, Y., Jia, F., Jiang, J. (2020). Design and test of chopping stalk crushing device for corn harvester cutting table (玉米收获机割台砍劈式茎秆粉碎装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.51, issue 7, pp.109-117, Harbin/China.

[15] Xin S., (2020), Study on the mechanism and key technology of corn ear picking with vertical roller (立辊采摘玉米穗机理及关键技术研究). *Gansu Agricultural University*, Lanzhou/China.

[16] Zhao, H., Ning, T., Nie, L., Wang, B., Tian, S., li, Z. (2013). Comparison of yields and nutrient compositions between different harvesting heights of maize stover (玉米原茬地秸秆还田比例调节装置设计与试验).*Scientia Agricultura Sinica*, Vol.46, issue 20, pp.4354-4361, Tai'an/China.

[17] Zhang, J., Yu, Y., Yang, Q., Zhang, J., Zhang, Z., Geng, A. (2018), Design and Experiment of Smashed Straw Unit for High Stubble Maize Double Header (全量秸秆粉碎条铺与种带分型清秸装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.49, issue s1, pp.42-49, Ta'ian/China.

[18] Zhang, F., Song, X., Zhang, X., Zhang, F., Wei, W., Dai F. (2019). Simulation and experiment on mechanical characteristics of kneading and crushing process of corn straw (玉米秸秆揉丝破碎过程力学特性仿真与试验). *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, Vol.35, issue 9, pp58-65, Gansu/China.

[19] Zhang, Z., Yu, Y., Yang, Q., Geng, A., Zhang, J. (2020). Development and evaluation of the finger wheel and cutting disc combined device for stalk returning. *INMATEH-Agricultural Engineering*, Vol.64, issue 2, pp.54-64, Ta'ian/China.

[20] Zahid, F.B., Zhi, C.O., Khoo, S.Y. (2020). A review of operational modal analysis techniques for in-service modal identification. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol.42, issue 8, Kuala Lumpur/Malaysia.