DESIGNING A LONGITUDINAL HOB-TYPE STALK CHOPPING DEVICE FOR CORN COMBINE HARVESTER
/
玉米联合收获机纵置滚刀式茎秆切碎装置的设计与试验

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ABSTRACT
At present, the quality of chopping stalks with the use of a corn combine harvester needs improvement. Therefore, this study aims at designing a hob-type stalk chopping device to be installed under the header which can realize multiple groups of parallel longitudinal arrangements. Moreover, the device will be able to cut and crush the root and the middle and upper parts of the stalks. The performance of a finite element analysis corroborated the satisfactory strength and stiffness of the designed chopping blade as the mechanical requirements. Moreover, the influencing working and structural parameters were determined using a theoretical analysis. Regarding the test factors, i.e., the tip angle of the blades, fixed angle and the rotational speed of chopper shaft, single-factor and central composite design tests were also performed. Furthermore, the percentage of the qualified length of chopped stalk and the power consumption of cutting stalk were taken as the evaluation indexes. Accordingly, the results revealed the influencing parameters to be ordered as the spindle speed > fixed angle > tip angle of the blades. Subsequently, the parameters were optimized using the response surface method. Based on the obtained results, the optimized parameters including the spindle speed, the fixed angle and the tip angle of the blades were specified as 1050 r/min, 56°, and 40°, respectively. The experimental validation was also carried out on the optimal combination of the parameters. The qualified lengths of the chopped stalks were found to be 92.9%, which were consistent with the predicted results of the model. Hence, the test results met the design requirements.

摘要
针对目前玉米联合收获机茎秆切碎质量低的问题，设计了一种可以安装在割台下方的滚刀式茎秆切碎装置，该装置可实现多组并行纵向布置，实现对茎秆根部和中上部的分别切割粉碎。运用 SOLIDworks 软件建立茎秆切碎装置模型，运用 ANSYS 软件对切断刀片和切碎刀片进行有限元静力学分析，结果表明刀片的强度刚度满足力学要求。通过对切碎茎秆过程动力学分析得到影响茎秆切碎效果的作业参数和结构参数。采用单因素和二次通用旋转组合试验，以刀尖刃角、刀片安装角、刀轴转速作为试验因素，以茎秆切碎长度合格率和切割功耗作为评价指标。结果表明，影响茎秆切碎长度合格率和切割功耗的主次因素为：刀轴转速 >刀片安装角 >刀尖刃角。采用多目标优化算法进行参数优化，优化结果为：刀轴为 1050r/min，刀片安装角为 56°，刀尖刃角为 40°。以优化后参数组合进行试验验证，茎秆粉碎长度合格率达到 92.9%，与预测值相近，满足设计要求。

INTRODUCTION
The annual corn stalk yield of China is estimated to be about 1.2×10^9 t *(Zhao et al., 2019)*. One of the main methods of harvesting corn stalk is crushing and returning it back to the field *(Li et al., 2015)*. Thus, inspecting this method of harvesting corn stalk is highly significant. Accordingly, numerous studies have investigated the cutting characteristics of the stalk as well as the features of the crushing device.

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This is particularly the case for the structure of the crushing tool which have been extensively examined. As examples, the use of such different structures as the Y-type structure *(Pan et al., 2015*), the V-L-type structure (*Jia et al., 2015*), the hammer claw type structure (*Yao et al., 2010*) as well as the other types (*Jiang et al., 2019; Tian et al., 2017*) can be mentioned for designing the swing knife. As a result, the quality of stalk crushing is rather improved. However, being mainly designed on the horizontal axis, stalk crushing devices are restricted by a number of parameters including the axis length. Accordingly, their use on the multi-row corn harvesters is limited. To resolve this problem, stalk crushing devices with vertical shaft structures are designed. The examples are the chopping stalk crushing machine and the chopping machine using an L-shaped cutting knife flicking *(Wang et al., 2020; Tian et al., 2022)*. Although the machines can be used for multi-row models, they suffer from poor practicality. Corn stalk is made of a type of anisotropic material, with different mechanical properties at its different parts and directions (*Meng et al., 2005; Wang et al., 2015*). This is to say that, cutting and crushing the root of the stalk requires greater force *(Gu et al., 2020),* while the horizontal axis and vertical axis stalk cutting and crushing devices crush the powder in the root and middle and upper part of the stalk in the same way, which also affects the effect of stalk crushing and returning to the field.

Therefore, considering the mechanical characteristics of the stalk as well as the problem of two layout structures, a hob-type stalk chopping device which can be installed under the header is designed in this study. Moreover, multiple groups of parallel longitudinal layouts can be realized using the proposed device. In addition, the proposed device will be able to cut and powder crush the roots as well as to separate the middle and the upper parts of the stalks. Furthermore, performing the finite element analysis, the designed chopping blade met the required mechanical properties, i.e., the strength and the stiffness. Also, the analysis of the cutting stress on the stalk determined the key factors affecting the cutting length of the stalk. Single factor test, ternary quadratic regression general rotation combination test and response surface method were performed to optimized the test factors. The best combination of the influencing parameters was also specified. The findings of the study can be used by future studies in developing stalk chopping machines for corn combine harvester.

MATERIALS AND METHODS

Structure and working mechanism

As can be seen in Fig.1, the stalk chopping device is composed of a cutting mechanism and a chopping mechanism. The former mechanism comprises a cutting blade, a grass cutting blade and a knife rest, which is used to cut off the root of the corn stalk. The grass cutting blade is located opposite the swing knife, in a triangular shape, with blades on its both sides. The function of the blade is to cut the ground weeds before cutting the root of corn stalk. As a result, the weeds are prevented from winding around the blade and negatively affecting the operation process. The cutting blade is trapezoidal. To ensure the root-cutting of the corn stalk during the normal operation, four cutting blades are located and evenly distributed around the cutting tool holder. On the other hand, being the core part of stalk chopping, the latter mechanism, i.e., the chopping mechanism, includes the chopping moving blade, chopping fixed blade, spindle and knife rest, the function of which is chopping the corn stalk. To make the dismantling and maintenance of the blade convenient, the chopping mechanism adopts the form of a combined installation of the knife rest and the blade. Moreover, the tool holder is designed into a hexagon shape, the circumference of which is equally divided into six points for installing the blades. Depending on the specific condition, either two, three or six blades are installed. Therefore, the more the number of the blades are, the shorter the cutting length of the stalk becomes.

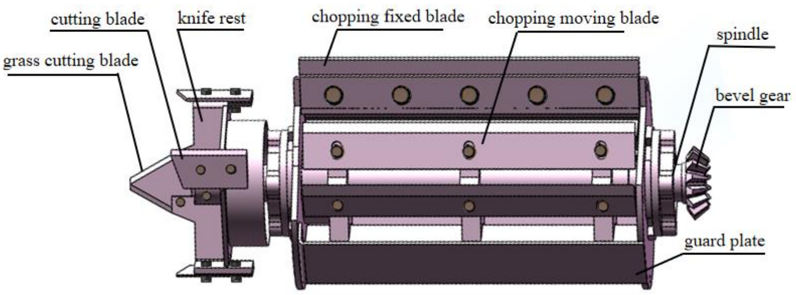


Fig. 1 - Structure diagram of stalk chopping device

The stalk chopping device is located under the header and is connected to it through a connecting plate. Thus, they work in conjunction with each other. Fig. 2 displays the installation position of the device. The cutting and the chopping mechanisms rotate in the same direction, at the same speed, and round the same axis.

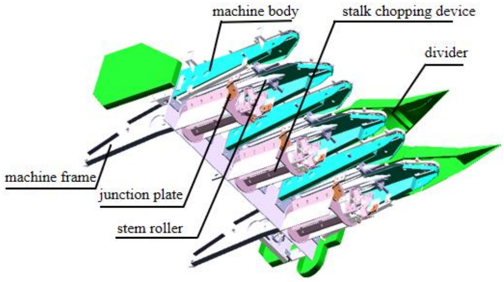


Fig. 2 - Installation diagram of stalk chopping device

Dynamic analysis

When the stalk chopping device is operating, the stalk is hit by the high-speed rotating chopping moving blade. According to the Work-Energy Theorem, the network done is calculated as:

$$F \cdot t = m\left(v_1 - v_0\right) \tag{1}$$

$$v_1 = \frac{\pi nR}{30} \tag{2}$$

Where:

F denotes the force (N); t stands for the cutting time (s); m represents the mass of corn stalk (kg);

v_1 suggests the final velocity (m/s); v_0 is the initial velocity (m/s); n signifies the spindle speed (r/min);

R means the distance from the tip of the blade to the centre of rotation (m).

The analysis of the stalk chopping is shown in Fig. 3, where α denotes the tip angle of the blades, and β stands for the fixed angle. Formula (1) can be used to calculate the relative speed of the stalk crushing device when it remains constant. The cutting force of the stalk is inversely proportional to the cutting time. Moreover, the cutting time is related to the hardness of stalk. In other words, the greater the hardness of the stalk is, the shorter the cutting time becomes *(Chen, et al., 2015; Wang, et al., 2017)* and the greater cutting force is required.

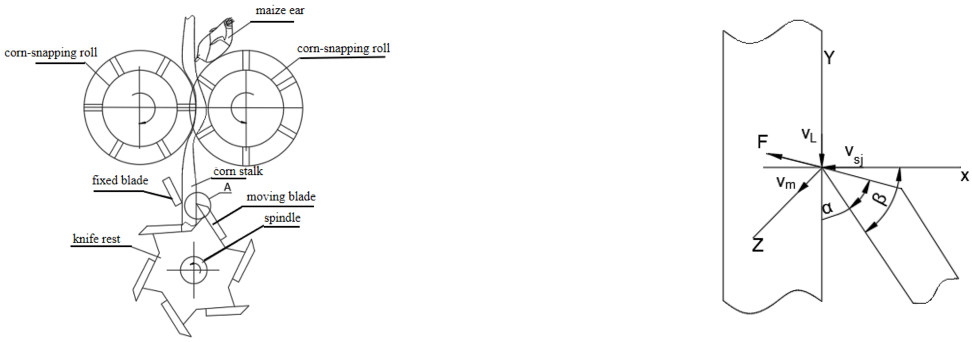


Fig. 3 - Analysis diagram of stalk chopping

Assuming that all of the impact load of the stalk crushing device is applied on the corn stalk, the critical conditions under which the stalk fracture is caused is as follows:

$$F \geq \tau_S A \tag{3}$$

Where:

τ_S denotes the ultimate stress of the stalk fracture, (N);

A represents the acting area of the stalk and the blade, (m^2).

Disregarding the curvature of the blade to the stalk contact surface, the action area of the stalk is calculated as:

$$A = \frac{\pi R_1^2}{\cos(\beta - \alpha)} \tag{4}$$

Where:

R_1 is the radius of stalk cross-section, (m).

According to formula (1) - (4), the critical condition for the stalk rupture is:

$$\frac{F}{A} = \tau = \frac{m(\pi nR - 30V_0)\cos(\beta\text{-}\alpha)}{30\pi t r^2} \geq \tau_s \tag{5}$$

where: τ denotes the shear stress, (Pa); β represents the fixed angle, (°); α suggests the tip angle of the blades.

According to Formula (5), the cutting fracture of the stalk occurs under the cutting force of high-speed rotating blade. This is directly proportional to the cosine value of the difference between the blade's speed, its installation angle and the tip angle. Moreover, the cutting fracture is inversely proportional to the cross-sectional area of the stalk at the cutting point. Therefore, it can be argued that the key to the improvement of the stalk cutting device is the specification of the best spindle speed and the blade angle.

The cutting length of the stalk can be expressed as:

$$L_0 = (1\text{-}\mu)\frac{2\pi \cdot n_l \cdot r_l}{n \cdot z} \tag{6}$$

where: μ denotes the coefficient of slippage between the stalk roller and the stalk;

r_l stands for the radius of the pull stalk roll, (m);

n_l represents the pull stalk roll speed, (r/min).

According to Formula (6), the cutting length of the stalk is directly proportional to the rotation speed and the radius of the pull-roll. Also, it is inversely proportional to the rotation speed of the cutter shaft and the number of blades in the circumferential direction. To meet the national standard requirements of straw cutting and grinding length, the other parameters were substituted into the formula to obtain L_0=64.1mm<100mm, which met the national standard requirements of straw cutting and grinding length.

Finite element analysis of blades

The reliability of the blade directly affects the working efficiency of the device when chopping the stalks. The cutting blade is designed as a rectangular trapezoid, the length of the cutting blade is determined as 110 mm. The thickness of the blade is one of the main influencing factors. Regarding the Structural steel characteristics of the stalk and the strength requirements of the blade, the thickness of the designed blade is determined as 4 mm. The length and the width of the designed chopping blade are determined as 430 mm and 55 mm, respectively. This is to ensure that the blade is able to cut the stalk when entering the ear picking roller, and accordingly, chop it back to the field. Moreover, the thickness of the designed blade is specified as 10 mm *(Zhang, et al., 2020)*. The material properties of the cutting blade and the chopping blade are described in Table 1. A finite element analysis was conducted on the blade after being meshed.

Table 1

Material parameter

Material	Poisson's Ratio	Elastic Modulus	Density	Yield Strength
		MPa	Kg/m³	MPa
Structural steel	0.3	2.0×10^5	7.85×10^3	305
65 Mn	0.282	1.97×10^5	7.81×10^3	785

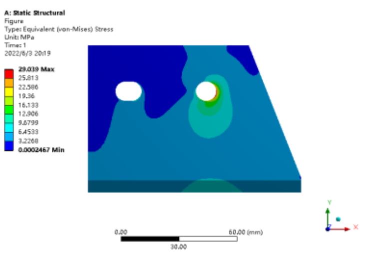


Fig. 4 - Stress nephogram of the cutting blade

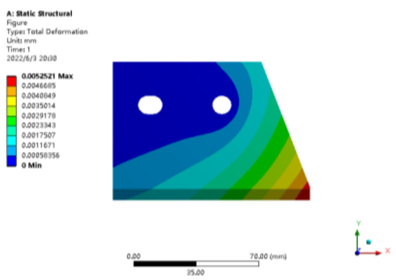
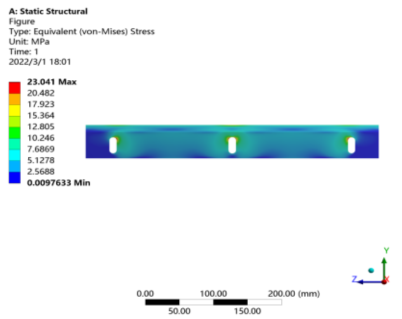


Fig. 5 - Total deformation nephogram of the cutting blade

As it is shown in Fig. 4, the stress of the cutting blade is distributed. The maximum stress on the blade (29.029 MPa) is observed at the threaded hole on the right side. Thus, the strength of cutting blade meets the requirements of mechanical properties.

Furthermore, as can be seen in Fig. 5, the total deformation of the cutting blade is distributed, the maximum displacement of which (0.0052521 mm) can be observed at the tip of the blade. Accordingly, within the safe range, the deformation resistance of the blade is satisfactory. Hence, it can be argued that the designed cutting blade ensures its constant and stable function.



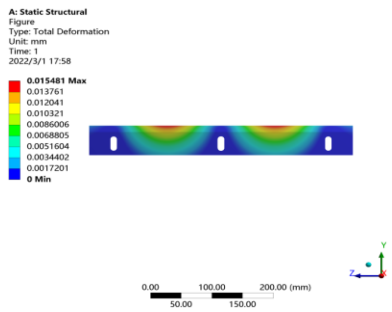


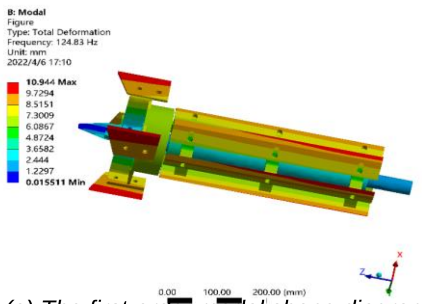
Fig. 6 - Stress nephogram of the chopping blade **Fig. 7- Total deformation nephogram of the chopping blade**

As can be seen in Fig. 6, the maximum stress value of the chopping moving blade is 23.041 MPa, which is considerably less than 355 MPa. Moreover, according to Fig. 7, the total deformation of the chopping blade (0.015481 mm) is distributed and falls within the safe range. Hence, it can be argued that the design of the chopping moving blade ensures its constant and stable function.

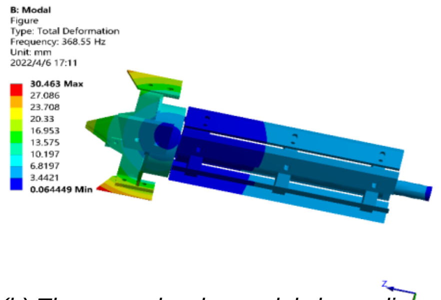
Modal analysis of the stalk chopping device

Due to the high rotational speed, the shaft of the stalk chopping device can easily produce vibration. Therefore, modal analysis of stalk chopping device was carried out. The first six-order natural frequencies and the vibration forms were simulated using the modal module of ANSYS Workbench software *(Zhang, et al., 2020).* Subsequently, to provide the theoretical basis for the optimization of the design of the device, the obtained results were compared and the vibration frequencies of excitation source were analysed.

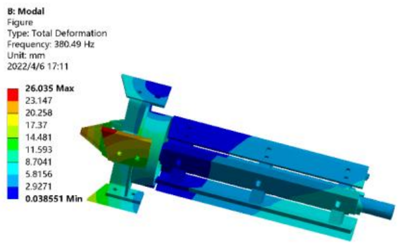
Fig. 8 displays the first sixth-order modes of the Modal module solved by ANSYS. Moreover, the sixth-order mode of the stalk chopping device and its corresponding vibration modes are listed in Table 3. As can be seen, the bending deformation and torsional deformation are the main vibration modes of the first six modes of the stalk chopping device. According to Table 3, the design speed of the stalk chopping device is 1600-2500 r/min, which is converted to a frequency of 26.69-41.67 Hz, i.e., lower than the lowest natural frequency of the cutter shaft (124.83 Hz). Hence, no resonance was observed.



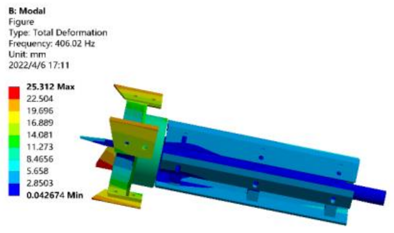
(a) The first-order modal shape diagram



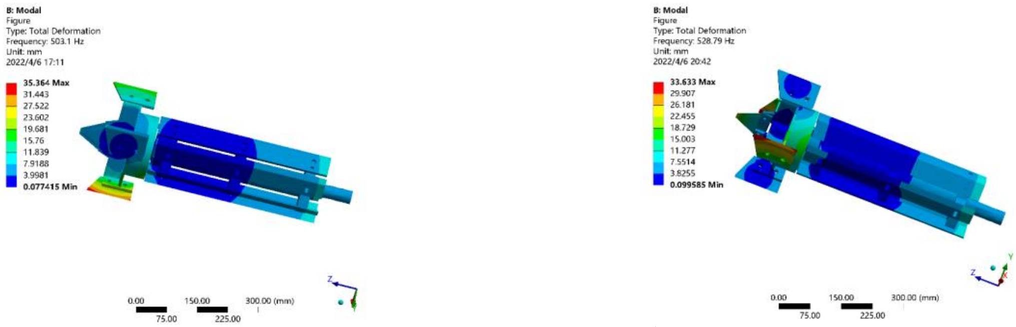
(b) The second-order modal shape diagram



(c) The third-order modal shape diagram



(d) The fourth-order modal shape diagram



(e) The fifth-order modal shape diagram （f）The sixth-order modal shape diagram

Fig. 8 - Sixth-order Modal Shape Diagram of the stalk chopping device

Table 2

Natural frequency of the first six modes of stalk chopping device

Mode Order	Frequency (Hz)	Vibration mode
1	124.83	Torsion vibration
2	368.55	Bending vibration
3	380.49	Bending vibration
4	406.02	Torsion vibration
5	503.1	Bending vibration
6	528.79	Bending vibration

Test equipment

In order to study the crush quality of stalk chopping device under certain combination of working parameters, a stalk shredding performance test was conducted on a self-built test bench of stalk shredding mechanism. The structure of the test bench is shown in Fig. 9.

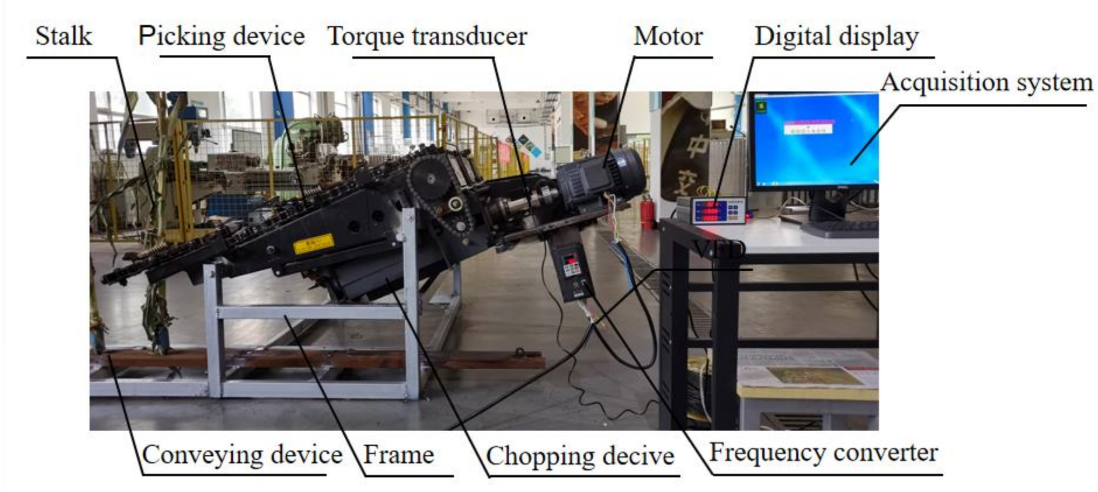


Fig. 9 - Test bench of stalk chopping device

Experimental design

According to the obtained results, the tip angle of the blades, the fixed angle and the spindle speed were selected as the experimental factors, and were determined as 30-50°, 0-60°, and 1000-2000 r/min, respectively. Each group of tests was repeated for three times. The average value of the obtained results was also calculated.

Performance evaluation

In accordance with the relevant standards of the GB/T 21962-2020 corn combine harvester, the performance of the harvester was evaluated based on the percentage of the chopped stalks with the qualified lengths and load power consumption. This was performed by modifying the experimental factors according to the experimental design scheme, feeding the machine with the stalks when it runs stably, and finally, collecting and counting the chopped stalks.

Therefore, the evaluation indexes were calculated based on the following formulas:

$$F_1 = \frac{M_z - M_b}{M_z} \times 100 \tag{7}$$

Where:

F_1 denotes the percentage of the chopped stalks with the qualified lengths, (%);
M_Z represents the weight of the stalks before being crushed, (kg);
M_b stands for the weight of the stalks whose lengths were greater than 100 mm, (kg).

$$p_J = p_Z - p_K = \frac{(T_Z - T_K)n}{9.55} \tag{8}$$

Where:

p_J denotes the power consumption of cutting stalk, (W);
p_z represents the total power consumption, (W);
p_K represents the no-load power consumption, (W);
T_z represents the total torque, (N·m);
T_k represents the no-load torque, (N·m);
n represents the rotational speed, (r/min).

RESULTS AND ANALYSIS

Single-factor test

Effect of tip angle of the blades

The fixed angle of the blade, the spindle speed and the moisture content of the corn stalk were set at 50°, 1000 r/min and 52.55%~53.78%, respectively. Moreover, the tip angle of the blade was adjusted to 30°, 40° and 50°, and the data were shown in Fig. 10.

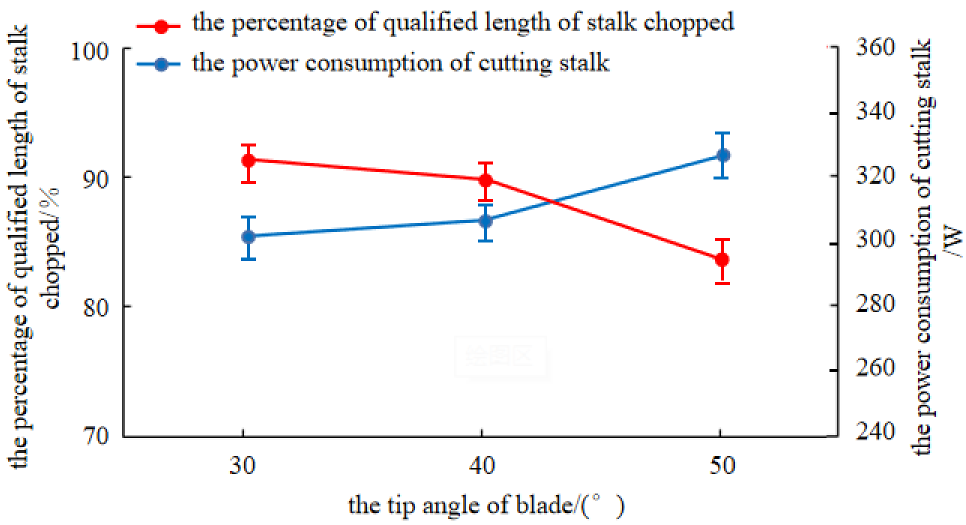


Fig. 10 - Influence of tip angle of the blades

As can be observed in Fig. 10, an increase in the tip angle of the blades led to a decrease in the qualified rate of the stalk cutting length and an increase in the power consumption of cutting stalk when the tip angle was 30~50°. While smaller angles facilitated the penetration of the blade into the stalk surface, larger angles hindered its penetration into the stalk epidermis.

Effect of fixed angle

The spindle speed, the blade edge angle and the moisture content of the corn stalk were set at 1000r/min, 40° and 52.55%~53.78%, respectively. Moreover, the fixed angle of the blade was adjusted to 0°, 10°, 20°, 30°, 40°, 50° and 60°, and the data were shown in Fig. 11.

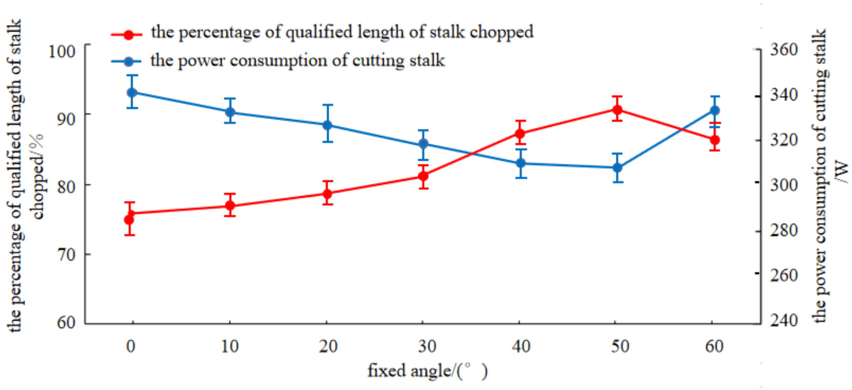


Fig. 11 - Influence of fixed angle

As can be seen in Fig. 11, an increase in the angle of blade led to an increase in the qualified rate of the cutting length of the stalk first. However, it subsequently decreased, an increase in the angle of blade led to a decrease in the power consumption of cutting stalk first.

However, it subsequently increased. Accordingly, it can be concluded that the installation of the blade at 40°-60° yielded the highest percentage of chopped stalks with the qualified lengths and the lowest power consumption of cutting stalk.

Effect of spindle speed

The fixed angle of the blade, the tip angle and the moisture content of the corn stalk were set at 50°, 40° and 52.55%~53.78%, respectively. Moreover, the spindle speed was adjusted to 800, 850, 900, 1000, 1050 and 1100, and the data were shown in Fig. 12.

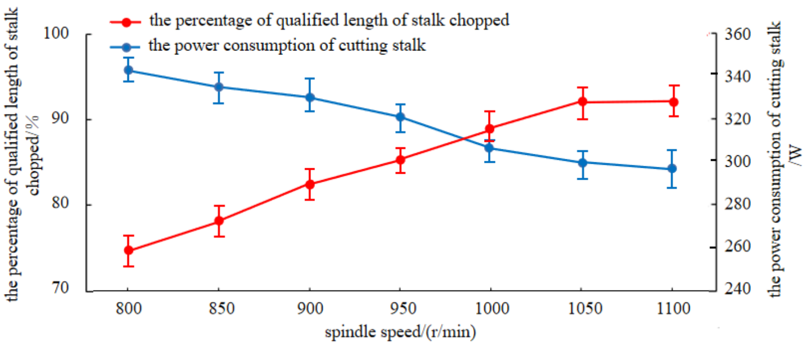


Fig. 12 - Influence of spindle speed

As can be seen in Fig.12, an increase in spindle speed led to an increase firstly and then it was steady in the qualified rate of the stalk cutting length. When the spindle speed reached 1100 r/min, it subsequently decreased. An increase in spindle speed led to a decrease in the power consumption of cutting stalk when the spindle speed remained between 800-1100 r/min. Furthermore, the spindle speed of 900-1100 r/min demonstrated the highest percentage of the chopped stalks with the qualified lengths and the lowest power consumption of cutting stalk.

Multi-factor test

To obtain the optimal combination of the working parameters for the stalk shredder, an orthogonal rotation test was performed on the Box-Behnken experimental method. According to the single results, the level of each factor was demonstrated in Table 3.

Table 3

Experimental factors and levels

Levels	Tip angle of the blades X_1 [°]	Fixed angle X_2 [°]	Spindle speed X_3 [r/min]
+1.68	50	60	1100
+1	46	56	1059.5
0	40	50	1000
-1	34	44	940.5
-1.68	30	40	900

The test scheme and the results are shown in Table 4. Design-Expert 8.06 software was applied to analyse the collected data.

Table 4

Test plan and results

Test No.	Tip angle of the blades X_1	Fixed angle X_2	Spindle speed X_3	Crushing length pass rate Y_1	Power consumption of cutting stalk Y_2
	[°]	[°]	[r/min]	[%]	[W]
1	-1	-1	-1	84.00	320.75
2	1	-1	-1	82.34	330.32
3	-1	1	-1	85.83	325.40
4	1	1	-1	89.20	316.88
5	-1	-1	1	90.1	288.45
6	1	-1	1	88.90	309.14
7	-1	1	1	91.50	278.54
8	1	1	1	90.00	300.38
9	-1.68	0	0	89.40	307.80
10	1.68	0	0	88.30	324.23
11	0	-1.68	0	92.00	330.34
12	0	1.68	0	92.20	297.85
13	0	0	-1.68	83.00	340.37
14	0	0	1.68	91.50	276.50
15	0	0	0	92.54	280.57
16	0	0	0	91.36	275.26
17	0	0	0	94.52	279.42
18	0	0	0	93.65	290.06
19	0	0	0	91.21	285.52
20	0	0	0	90.43	280.86

Analysis of results

The variance analysis results of the percentage of the qualified length of chopped stalk are shown in Table 5. According to the results, while the regression model was significant, no incompatibility was observed. Moreover, the regression model for the pass rate of the percentage of the qualified length of chopped stalk was established using formula 9. Accordingly, the fit coefficient (R^2) was 0.8674, the factors influencing the percentage of the qualified length of chopped stalk were found to be ordered as the spindle speed X_3 > fixed angle X_2 > tip angle of the blades X_1.

$$Y_1 = 92.33 - 0.21X_1 + 0.84X_2 + 2.45X_3 + 0.59X_1X_2 - 0.55X_1X_3 - 0.77X_2X_3 - 1.53X_1^2 - 0.38X_2^2 - 2.09X_3^2 \quad (9)$$

Where:

X_1 denotes the tip angle of the blades, (°);
X_2 represents the fixed angle, (°);
X_3 stands for the spindle speed, (r/min).

Table 5

Variance analysis results of the percentage of the qualified length of chopped stalk

Sources	Squares	DF	MS	F value	P value
Model 1	190.83	9	21.20	7.27	0.0023
x_1	0.59	1	0.59	0.20	0.6623
x_2	9.73	1	9.73	3.33	0.0978
x_3	81.81	1	81.81	28.04	0.0003
x_1x_2	2.80	1	2.80	0.96	0.3506
x_1x_3	2.43	1	2.43	0.83	0.3828
x_2x_3	4.79	1	4.79	1.64	0.2290
x_1^2	33.70	1	33.70	11.55	0.0068
x_2^2	2.08	1	2.08	0.71	0.4180
x_3^2	63.24	1	63.24	21.68	0.0009
Residual	29.17	10	2.92		
Lack of Fit	16.80	5	3.36	1.36	0.3729
Pure Error	12.38	5	2.48		
Cor Total	220.00	19			

*Note: P<0.01(extremely significant,**), P<0.05(significant,*).*

Fig. 13 shows that when the fixed angle remains constant and the spindle speed is in the range 900-1100 r/min, the percentage of the chopped stalks will gradually increase with increasing spindle speed; on the other hand, when the spindle speed remains constant and the fixed angle varies in the range 40-60 mm, the percentage of the chopped stalks gradually increases with increasing fixed angle. The response surface changes faster in the direction of spindle speed than in the direction of fixed angle.

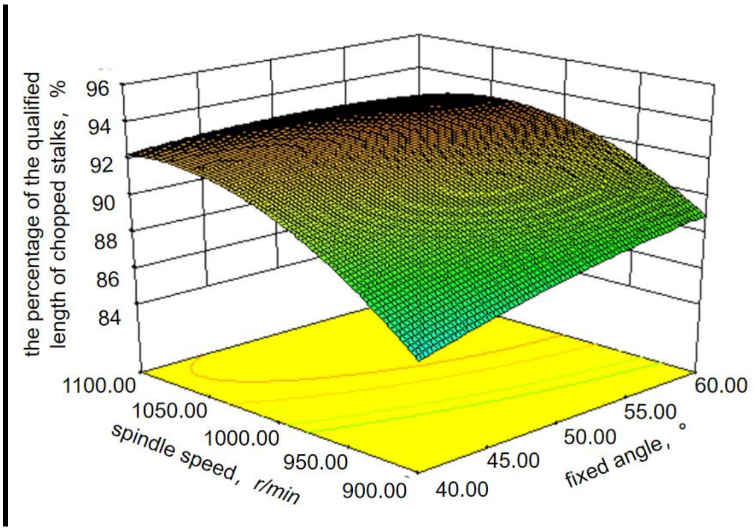


Fig. 13 - Impact of spindle speed and tip angle of the blades on the percentage of the chopped stalks

The variance analysis results of the power consumption of cutting stalk are shown in Table 6, the regression model for the power consumption of cutting stalk was established using formula 10. Accordingly, the fit coefficient (R^2) was 0.9442, the factors influencing the consumption were found to be ordered as the spindle speed X_3 > fixed angle X_2 > tip angle of the blades X_1.

$$Y_2 = 282.14 + 5.21X_1 - 6.01X_2 - 16.42X_3 - 2.12X_1X_2 + 5.19X_1X_3 - 1.23X_2X_3 + 10.78X_1^2 + 10.10X_2^2 + 8.10X_3^2 \quad (10)$$

Table 6

Variance analysis results of the power consumption of cutting stalk

Sources	Squares	DF	MS	F value	P value
Model 2	8239.07	9	915.45	18.80	<0.0001
x_1	371.32	1	371.32	7.63	0.0201
x_2	493.57	1	493.57	10.14	0.0098
x_3	3682.46	1	3682.46	75.64	<0.0001
x_1x_2	35.87	1	35.87	0.74	0.4108
x_1x_3	215.07	1	215.07	4.42	0.0619
x_2x_3	12.20	1	12.20	0.25	0.6275
x_1^2	1674.81	1	1674.81	34.40	0.0002
x_2^2	1470.53	1	1470.53	30.20	0.0003
x_3^2	945.61	1	945.61	19.42	0.0013
Residual	486.85	10	48.69		
Lack of Fit	354.08	5	70.82	2.67	0.1527
Pure Error	132.77	5	26.55		
Cor Total	8725.93	19			

*Note: P<0.01(extremely significant,**), P<0.05(significant,*).*

Fig. 14 shows that when the tip angle of the blades remains constant and the spindle speed is in the range 900-1100 r/min, the power consumption of cutting stalk will gradually decrease with increasing spindle speed; on the other hand, when the spindle speed remains constant and the tip angle of the blades varies in the range 30-50°, the power consumption of cutting stalk gradually increases with increasing tip angle of the blades.

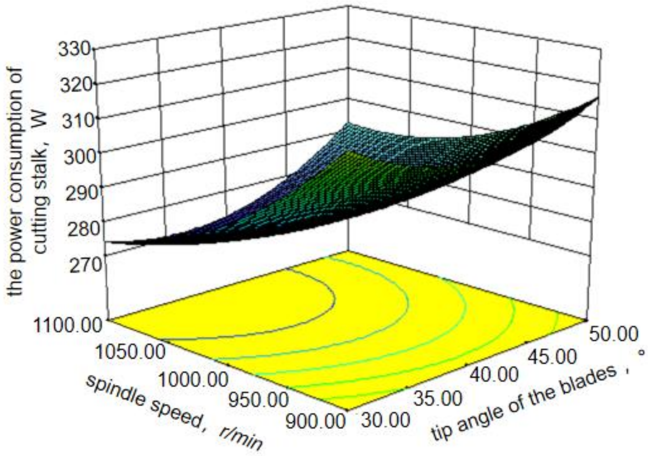


Fig. 14 - Impact of tip angle of the blades and spindle speed on the power consumption of cutting stalk

Parameter optimization and validation

To obtain the best working parameters of the stalk shredder, the maximum crushing length pass rate and the minimum power consumption of cutting stalk were taken as the optimization objectives. Accordingly, the optimization module in Design-Export 8. 0. 6 software was used to achieve the optimal parameters. The objective function and constraint conditions are expressed in formula (11):

$$\begin{cases} \max y_1(x_1, x_2, x_3) \\ \min\ y_2(x_1, x_2, x_3) \\ \text{s.t.} \begin{cases} 30° \le x_1 \le 50° \\ 40° \le x_2 \le 60° \\ 900 r/\min \le x_3 \le 1100 r/\min \end{cases} \end{cases} \tag{11}$$

The optimal working parameters, including the tip angle of the blades, the fixed angle and the spindle speed, were determined as 39.52°, 55.67° and 1048.92 r/min, respectively. Moreover, the predicted value of the crushing length pass rate was 93.2%. For the convenience of calculation and measurement, the optimization results, i.e., the tip angle of the blades, the fixed angle and the spindle speed were rounded off to be 40°, 56° and 1050 r/min. Next, the validation experiment was carried out based on the above optimization parameters. As the result, the average qualified rate of crushing length of corn stalk was determined to be 92.9%, which was close to the predicted value (93.2%).

CONCLUSIONS

(1) A hob-type stalk chopping device was innovatively designed in the present study. SolidWorks software was utilized to establish the model of the stalk shredding device. Moreover, to carry out finite element static analysis as well as modal analysis, ANSYS software was applied. The results corroborated the strength and stiffness of the designed blade to meet the required mechanical properties. In addition, no resonance was found to occur in the device.

(2) Performing the kinetic analysis on the stalk cutting system, the main factors affecting the crushing length of the stalk were determined. Additionally, a test bench was established for the stalk chopping mechanism. Furthermore, the application of the variance analysis revealed the influencing parameters on the qualified rate of crushing length and power consumption of cutting stalk to be ordered as the spindle speed > > fixed angle > tip angle of the blades.

(3) Taking the maximum qualified rate of crushing length and the minimum power consumption of cutting stalk as the optimization objective, the optimal working parameters, i.e., the tip angle of the blade, the fixed angle and the spindle speed, were determined to be 40°, 56° and 1050 r/min, respectively. Moreover, a test was carried out according to the optimum parameter combination, the results of which revealed the average qualified rate of crushing length to be 92.9%, which was consistent with the prediction results of the model.

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