RESEARCH AND OPTIMIZATION OF PARAMETERS CONCERNING THE INTERACTION MECHANISMS BETWEEN VERTICAL CUTTING BLADES AND STRAW IN CORN COMBINE HARVESTERS
/
玉米联合收获机纵置切刀-秸秆互作机理研究与参数优化

Zhu ZHAO[1,2], Fengbo LIU[1], Dongli SHUI[1], Bintong ZHAO[3], Zhongnan WANG*[1]
[1]Liaoning Agricultural Technical College, Yingkou / China
[2] College of Agricultural and Animal Science, Tacheng Vocational and Technical College, Tacheng / China;
[3] College of Engineering, Shenyang Agricultural University, Shenyang / China;
Tel: +8604177020545; E-mail: zhaosynd@163.com
Corresponding author: Zhongnan Wang
DOI: https://doi.org/10.35633/inmateh-74-87

Keywords: *Corn harvester, longitudinal straw shredding device, bionic cutting blades, cutting mechanism analysis, cutter-straw cutting simulation, finite element analysis*

ABSTRACT
This study introduced a vertical straw shredding device that integrates both cutting and shredding functionalities, with the crucial components of the blade designed in a bionic serrated pattern. In order to explore the interaction mechanism between the vertical cutting blade and straw, a mechanical model of the cutting force has been developed. Based on the ANSYS-LYNA software, a cutting model for straw-bionic blades has been established. Regarding the test factors, i.e., the spindle speed, blade installation angle, forward velocity, and blade tilt angle, single-factor and orthogonal tests were also performed. Furthermore, the maximum equivalent stress experienced by straw was taken as the primary evaluation index. Accordingly, the results revealed the influencing parameters to be ordered as the blade installation angle> spindle speed > forward speed > blade tilt angle. The optimized parameters for the cutting blade were determined to be a spindle speed of 1400 r/min, an installation angle of 55°, a forward speed of 4.0 km/h, and a blade tilt angle of 0°. Similarly, the optimized parameters for the shredding blade were established as a spindle speed of 1400 r/min, an installation angle of 50°, a forward speed of 4.0 km/h, and a blade tilt angle of 0°.

摘要
本研究设计了一种集成切断和切碎功能于一体的纵向秸秆切碎装置，关键部件刀片设计为仿生刃形式。为探究纵置切刀-秸秆互作机理,建立纵置切刀切割力学模型.基于ANSYS-LYNA 软件建立秸秆-仿生切刀切割模型,以刀轴转速、刀片安装角、前进速度和刀片倾斜角等试验因素，以切断刀和切碎刀切割秸秆过程秸秆所受最大等效应力为评价指标进行单因素和四因素四水平正交试验。试验结果表明刀轴转速、切刀安装角及行进速度对秸秆所受最大等效应力有显著影响，显著性顺序为切刀安装角>刀轴转速>行进速度>刀片倾斜角，切断刀在试验因素范围内的较优参数组合为刀轴转速 1400r/min、刀片安装角 55°、行进速度 4.0km/h 及刀片倾斜角 0°，切碎刀在切割试验因素范围内的较优参数组合为刀轴转速 1400r/min、刀片安装角 50°、行进速度 4.0km/h、及刀片倾斜角 0°。

INTRODUCTION
The straw shredding mechanism, which acts as an essential element within the combine harvester, significantly improves its operational capabilities *(Liu et al., 2019)*. Generally, the design of straw shredding mechanisms is categorized as either vertical or horizontal *(Zhang et al., 2021)*, employing a singular blade to process the entire straw. The straw cutting device faces issues such as poor cutting quality, high operational power consumption, and a tendency for the blades to wear out easily. The cutting of straw is closely related to the resource utilization of crop residues. Conducting research on the interaction process of cutting blades and straw is a significant aspect of the deep integration of agronomy and agricultural machinery, which has practical implications for agricultural production and ecological development *(Wu et al., 2022; I. Aygun and E.Cakir, 2014)*.

[1] *Zhao Zhu, Prof. Ph.D. Eng.; Liu Fengbo, Prof. Ph.D. Eng.; Shui Dongli, Lab.Techo. MA. Eng.; Zhao Bintong, MA. Stud. Eng.; Wang Zhongnan, Lab.Techo. MA. Eng.*

The methodologies *employed* for straw cutting research are generally categorized into experimental and simulation approaches. Experimental investigations predominantly utilize mechanical testing apparatus *(Ren et al., 2018)*, texture analysis devices (*Huang et al., 2021)*, swing-cut testing platforms *(Song et al., 2016)*, or the establishment of dedicated cutting test configurations and field trials to assess the influence of cutting parameters on various evaluation metrics. Standard evaluation metrics encompass cutting power consumption and cutting force. Simulation studies offer advantages such as low cost and high efficiency, serving as an effective complement to experimental research. Finite element software like ANSYS/LS-DYNA has been extensively applied in simulation studies of straw cutting *(Gürkan Irsel, 2022)*. Wan et al. employed ANSYS/LS-DYNA to analyze the influence of device rotational speed, slope angle, and stem diameter on the maximum impact force and average power observed during the shredding process of mushroom grass *(Wan et al., 2023)*. Xiao et al. performed computational simulations of the sugarcane cutting mechanism utilizing ANSYS/LS-DYNA software. Their findings revealed that with a cutter line speed of 38.8 m/s, a blade disk tilt angle of 11.66°, and a cutting edge angle of 25°, the minimum cutting power necessary was determined to be 0.80 kW (*Xiao et al., 2022*). Sun et al. utilized ANSYS/LS-DYNA software to simulate the branch cutting process, comparing the results with the cutting force curves obtained from bench tests, and concluded that the simulation results aligned well with those from the bench experiments *(Sun et al., 2022)*. Zhang et al. employed ANSYS/LS-DYNA to investigate the rotary cutter's straw cutting process, identifying the parameters that minimize power consumption: a blade rotation speed of 1400 r/min, a cutting thickness of 7 mm, and a cutting edge angle of 20° (*Zhang et al., 2016)*. Moreover, ABAQUS *(Huang et al., 2021)*, the dynamic simulation software ADAMS, and discrete element method (DEM) technology *(Li et al., 2016; Chen et al., 2024)* have been utilized in various aspects of cutting performance research.

This study addresses the insufficient focus on the physical characteristics and cutting efficiency of straw shredding machinery, leading to issues like poor cutting quality, higher energy demands, and blade susceptibility. It proposes a design for a vertical straw shredding device equipped with biomimetic blades to enhance performance. It clarifies the cutting interaction dynamics between the vertical cutter and the straw, formulates a force model for the vertical cutter, and utilizes ANSYS-LYNA software to develop a biomimetic model of the cutter-straw interaction. The research performs simulation analyses of the cutting process involving the biomimetic cutter and straw, offering a theoretical basis for the design of straw shredding mechanisms in corn harvesting equipment.

MATERIALS AND METHODS

Structure and working mechanism

Considering the organizational structure and cutting characteristics of corn straw, a vertical straw shredding device has been engineered. This device is located below the ear-picking devices on the header, as depicted in Figure 1.

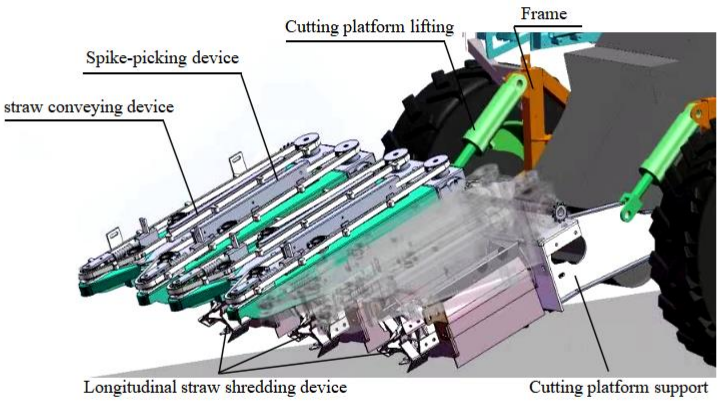


Fig. 1 - The installation diagram of longitudinal hob-type straw shredding device

The straw shredding device is composed of a cutting mechanism and a shredding mechanism. The cutting mechanism is made up of a cutting blade, a grass-cutting blade, and a cutting blade support. The shredding mechanism includes a shredding blade, shaft, and a shredding blade support, as illustrated in Figure 2. In the process of harvester operation, the blades of the cutting mechanism truncate the corn stalks at a reduced cutting height. As the harvester progresses, the stalks are directed into the shredding mechanism, where they are fragmented into smaller sections by the shredding blades.

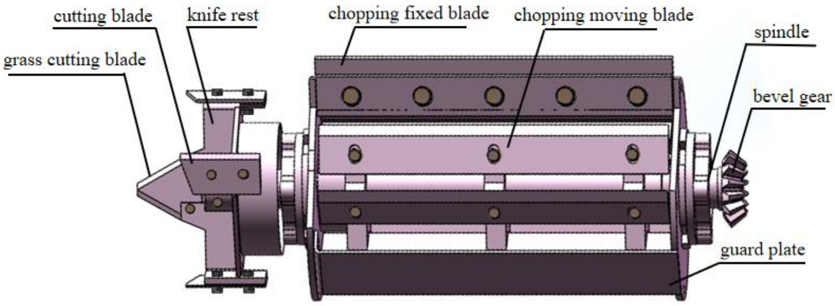
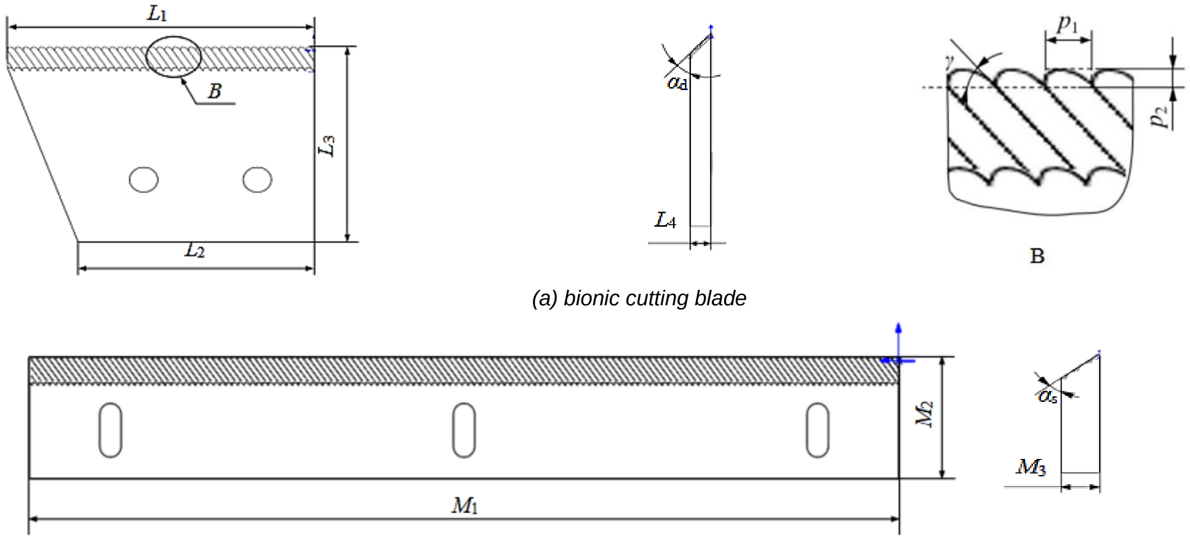


Fig. 2 - Structure diagram of straw shredding device

The cutting and shredding blades are engineered to emulate the mandibles of ants, featuring bionic serrations crafted into a suitable curvature that reflects the shape of the fourth tooth of an ant's jaw. The contour curve is expressed as a fifth-degree polynomial, and the configuration of the bionic blade is depicted in Figure 3, with specifications outlined in Table 1.



(a) bionic cutting blade

(b) bionic shredding blade

Fig. 3 - The structural of bionic blades

Note: p_1 represents the tooth spacing of the bionic blade, mm; p_2 indicates the tooth height of the bionic blade, mm; γ denotes the inclination angle of the tooth edge of the bionic blade, °.

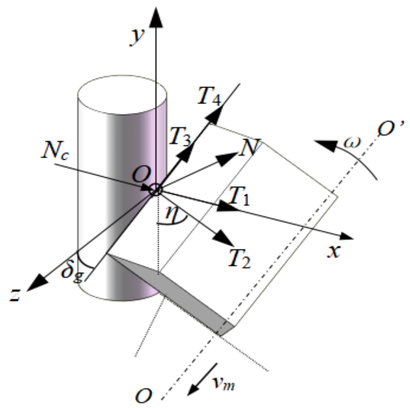
Table 1

The parameters of bionic cutting blade and shredding blade

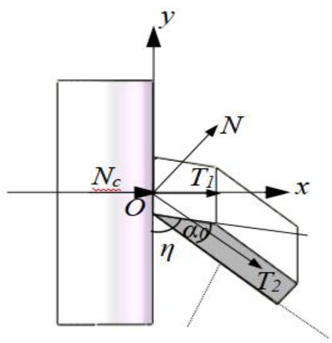
Project	Value	Project	Value
L_1/ mm	110	M_1 / mm	430
L_2 / mm	80	M_2 / mm	55
L_3 / mm	90	M_3 / mm	10
L_4 / mm	5	α_s / °	38
α_d / °	26	P_1/mm	3
Material of cutting blade	T10	Material of shredding blade	65Mn

Construction of the cutting mechanics model for vertically cutting blades

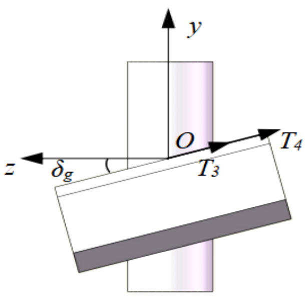
The cutting process of the vertically cutting blade experiences complex forces. To facilitate the analysis of the forces acting on the blade, a uniformly distributed load applied across the blade's edge is assumed, focusing on the forces present during the extrusion stage and the initial cutting initiation. Establish a force diagram for the vertical cutting blade in a three-dimensional coordinate system, where the *Oxy* plane serves as the primary cutting surface, and the *Oyz* plane represents the secondary cutting surface, as depicted in Figure 4.



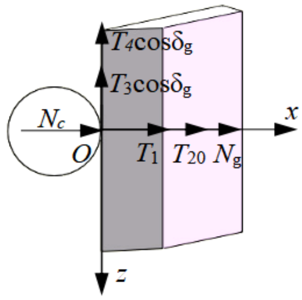
(a) The forces acting on the cutting blade



(b) Cutting blade stress in Oxy-plane



(c) Cutting blade stress in Oyz-plane



(d) Cutting blade stress in Oxz-plane

Fig. 4 -Force analysis diagram of longitudinal blade

Analysis of the compressive stress and construction of the mathematical model on the primary cutting plane

The compressive stress on the cutting blade at the primary cutting plane is illustrated in Figure 5.

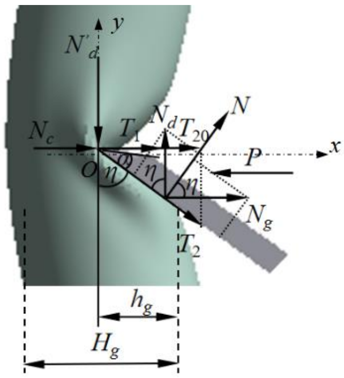


Fig. 5 -Force analysis of the main cutting surface of longitudinal blade

The reactive force *N* exerted on the cutting tool is:

$$N = N_g \cos\eta + N_d \sin\eta \tag{1}$$

where:

N represents the pressure reaction force of the vertical cutting blade, (N);

η denotes the blade installation angle, (°);

N_g stands for the horizontal reaction force N_d exerted on the vertical cutting blade, (N);

N_d represents the vertical reaction force exerted on the vertical cutting blade, (N);

In the presence of the counteracting force N, the cutting tool produces a tangential frictional force T_2.

$$T_2 = \mu_1 N = \mu_1 (N_g \cos\eta + N_d \sin\eta) \tag{2}$$

where:

T_2 represents the tangential frictional force applied to the cutting blade, (N);

μ_1 represents the horizontal friction coefficient between the blade and the straw.

Under the influence of the vertical reaction force N_d, the cutting blade's other cutting surface experiences a frictional force T_1.

$$T_1 = \mu_1 N_d \tag{3}$$

The tangential friction component acting along the horizontal axis, denoted as T_{20}:

$$T_{20} = T_2 \sin\eta = \mu_1 (N_g \cos\eta + N_d \sin\eta) \sin\eta \tag{4}$$

It is clear that in the straw compression phase, the cutting blade is subjected to forces oriented horizontally along the x-axis. This encompasses the horizontal reaction force N_g induced by the compressed straw, the frictional force T_1 present on the blade's cutting surface, as well as the tangential friction force component T_{20} acting in the horizontal plane.

Analysis of the plastic deformation stress on the main cutting surface and the construction of a mathematical model

As the corn stalks experience plastic deformation, the cutting blade encounters a reaction force N_c:

$$N_c = \Delta_c L_c \sigma_c \tag{5}$$

where:

N_c denotes the reaction force of corn stalks on the cutting blade, (N);

Δ_c denotes the thickness of the cutting blade involved in the cutting process, (m);

L_c denotes the length of the cutting blade involved in the cutting process, (m);

σ_c denotes the critical yield strength of the corn straw, (N/m²).

To achieve the cutting of straw, the horizontal pressure P must meet the following conditions:

$$P \geq N_c + N_g + T_1 + T_{20} \tag{6}$$

By incorporating equations (3), (4), and (5) into equation (6), the minimum horizontal pressure, designated as P_{min}, is derived as follows:

$$P_{\min} = \Delta_c L_c \sigma_c + N_g + \mu N_d + \mu (N_g \cos\eta + N_d \sin\eta) \sin\eta \tag{7}$$

Integrate the forces dN_g and dN_d acting on the thickness of the compressed straw layer unit, as illustrated in Figure 6.

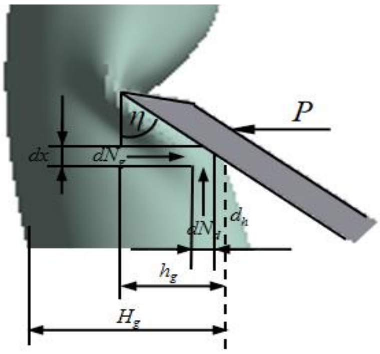


Fig. 6 - Integration force diagram of the main cutting surface

Assuming straw is regarded as an elastic material, according to Hooke's Law:

$$\varepsilon = \frac{\sigma}{E} = \frac{h_{gx}}{H_g} \tag{8}$$

where:

ε represents the relative deformation;

σ represents the normal stress experienced by the corn straw, (N/m²);

E represents the elastic modulus of the corn straw, (N/m²);

h_{gx} represents the depth of compression on the straw, (m);

H_g represents the total thickness of the straw cutting layer, (m).

In the lateral direction, the differential force dNg exerted on the blade is:

$$dN_g = \sigma dx = E\varepsilon dx = E\varepsilon \tan\eta dh_x \tag{9}$$

Integrating both sides of the above equation yields:

$$N_g = \frac{E}{H_g}\tan\eta\int_0^{h_g} h_x dh_x = \frac{E}{2H_g}h_g^2\tan\eta \tag{10}$$

The differential force acting on the cutter in the vertical direction:

$$dN_d = \varepsilon_1 E dh_x \tag{11}$$

where:

ε_1 represents the relative deformation of straw in the vertical direction. As is known from engineering mechanics:

$$\varepsilon_1 = \varepsilon\nu \tag{12}$$

Where:

ν represents the Poisson's ratio of corn stalks, (m).

Upon substituting equation (12) into equation (11) and performing integration on both sides of equation (11), the ensuing results are obtained.

$$N_d = \frac{\mu E}{H_g}\int_0^{h_g} h_x dh_x = \frac{E}{2H_g}h_g^2\mu \tag{13}$$

Where:

E denotes the elastic modulus of corn stalks, (N);

H_g denotes the compression depth of the stalk before cutting, (m);

μ denotes the Poisson's ratio.

By integrating equations (5), (10), and (13) into equation (7), the pressure P is derived:

$$P = \Delta_c\sigma_c + \frac{Eh_g^2}{2H_g}\left[\tan\eta + \mu\sin^2\eta + \nu\mu\left(1+\cos^2\eta\right)\right] \tag{14}$$

Analysis of force on the side cutting surface and the construction of a mathematical model

The cutting blade undergoes forces on the *Ozy* plane, as illustrated in Figure 7, where the underside of the blade creates a frictional force denoted as T_3.

$$T_3 = \mu_2 N = \mu_2(N_g\cos\eta + N_d\sin\eta) \tag{15}$$

where: T_2 represents the tangential frictional force experienced by the blade, (N);

μ_2 represents the coefficient of longitudinal friction between the blade and the straw.

The blade produces a frictional force T_4:

$$T_4 = \mu_2 N_d \tag{16}$$

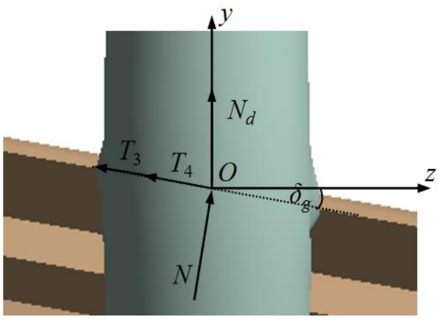


Fig. 7 - Force analysis of the secondary cutting surface of longitudinal blade

The component of friction acting in the direction of motion is:

$$T_0 = \left(T_3 + T_4\right)\cos\delta_g = \left[\mu_2(N_g\cos\eta + N_d\sin\eta) + \mu_2 N_d\right]\cos\delta_g \tag{17}$$

It is clear that the forces exerted on the secondary cutting edge of the blade are influenced by the intrinsic material characteristics, the angles of cutting, and the blade's angle of inclination.

Establishment of the Cutter - Straw Cutting Model

To analyze the impact of experimental variables, including shaft rotation velocity, blade installation angle, travel speed, and blade inclination angle, on the peak equivalent stress encountered by corn straw during the cutting operation, dynamic cutting simulation tests were performed to identify the optimal operational parameters for the straw shredding devices.

A set of blades is selected for simulation cutting, removing the bolted attachment that links the cutter to the spindle and establishing a rigid connection between them. Disregarding the differences in the transverse geometry of corn stalks, assuming that maize stalks are represented as a dual-layer orthogonal isotropic cylindrical configuration featuring a uniform cross-sectional area, with a diameter specified at 27 mm. The internal fibers are considered to be uniformly and systematically arranged along the axial direction, resulting in a linear structure, with the straw length designated at 100 mm. The external layer and internal pith of the corn straw are intricately fused, with the thickness of the outer skin set at 1 mm.

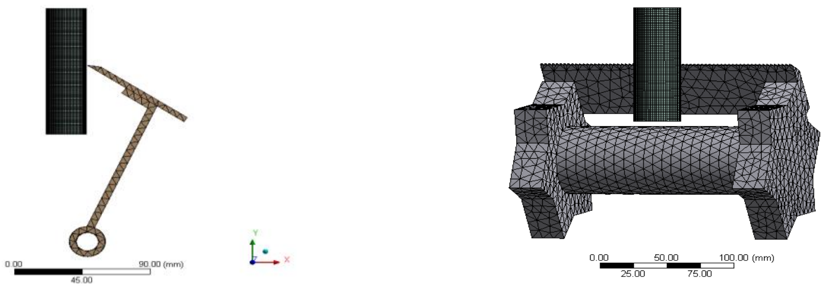
Apply full constraints to both the base and top of the straw, with the cutting position set at a distance from the lower-middle section of the straw. A dual-layer representation of corn straw and a blade model were created utilizing SolidWorks software, subsequently saving it in .x_t format for incorporation into ANSYS LS-DYNA. Given LS-DYNA's proficiency in conducting numerical simulations of abrupt impact events, the duration for these simulations remains comparatively brief. In the context of the cutting model, it is optimal for the clearance between the blade and the corn straw to be precisely calibrated for contact. The material model selected for corn straw is categorized as a transversely isotropic elastic material, with the parameters of its material properties detailed in Table 2.

Table 2

Material parameter of corn stalk

Part	Density/(kg·m^{-3})	Elastic modulus/MPa	Poisson's Ratio	Shear modulus	Maximum equivalent failure stress
Straw husk	1120	3845.7	0.3	734	0.2
Straw pith	830	41.83	0.1	133	0.2

In the grid division process, the properties of the cutting tool and the corn straw material are defined, treating the cutter as a rigid body while designating the corn straw as a flexible entity. Frictional interactions occurring during the cutting action necessitate the assignment of a dynamic friction coefficient of 0.22 and a static friction coefficient of 0.45. The Body Sizing methodology is utilized for the model's grid division. To enhance the precision of the solution, additional control measures are applied to the grid elements of the corn straw, with the element size calibrated to 1.0 mm. The grid segmentation for the cutting simulation has been finalized, as depicted in Figure 8.



(a) cutting model *(b) shredding model*

Fig. 8 - Model after meshing

The simulation duration is established at 0.005 seconds, with five CPUs designated and a memory allocation of 100 units. The output data is formatted as a series of equidistant points, each valued at 100, and the contact model selected is face-to-face erosion. Fixed constraints allowing full freedom of movement are imposed on both the top and bottom surfaces of the straw, effectively constraining any motion. Blade motion encompasses a combination of rotational movement around the blade's axis and longitudinal displacement. Specifically, the blade is programmed to translate along the Z-axis while simultaneously rotating about the Z-axis. The translation velocity is contingent upon the harvesting machine's operational speed and the stipulations of experimental design.

The rotational velocity of the blade shaft is modulated through variation in the blade's rotational angle, coupled with a distal displacement introduced at one end of the blade holder to restrict the plane of motion for the blade.

Experimental design

Single-factor experimental design

The blade installation angle is established at 50°, accompanied by a forward velocity of 3.0 km/h. The spindle rotation rates have been selected at 1000, 1200, 1400, 1600, 1800, and 2000 revolutions per minute to evaluate the resultant stress on corn stalks throughout the cutting operation. At a rotational speed of 1400 revolutions per minute and a feed rate of 3.0 kilometers per hour, various blade installation angles of 40°, 45°, 50°, 55°, 60°, 65°, and 70° are investigated to assess the peak equivalent stress experienced by corn stalks during the cutting process. When the blade installation angle is 55° and the spindle speed is 1400 r/min, the forward speeds are set at 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 km/h to measure the equivalent stress of corn stalks during cutting. With a spindle speed of 1400 r/min, a forward speed of 3.0 km/h, and a blade installation angle of 55°, the blade inclination angles of 0°, 10°, 20°, and 30° are assessed to obtain the maximum equivalent stress of corn stalks during cutting.

Multi-factor orthogonal experimental design

To achieve the most effective combination of operational parameters for cutter performance during the cutting process, the experimental variables encompass spindle speed, feed rate, cutter mounting angle, and cutter tilt angle. The maximum equivalent stress experienced by corn stalks during the cutting operation serves as the assessment criterion for the orthogonal experiments conducted.

RESULTS AND ANALYSIS

Single-factor test

Effect of shaft rotational speed

Figure 9 delineates the maximum equivalent stress experienced by corn straw within the rotational speed range of 1000 to 2000 r/min. As the shaft speed increases, the maximum equivalent stress values fluctuate. At a rotational speed of 2000 r/min, the maximum equivalent stress experienced by the cutting blade and shredding blade on the straw peaks at values of 182.2 MPa and 186.5 MPa, respectively.

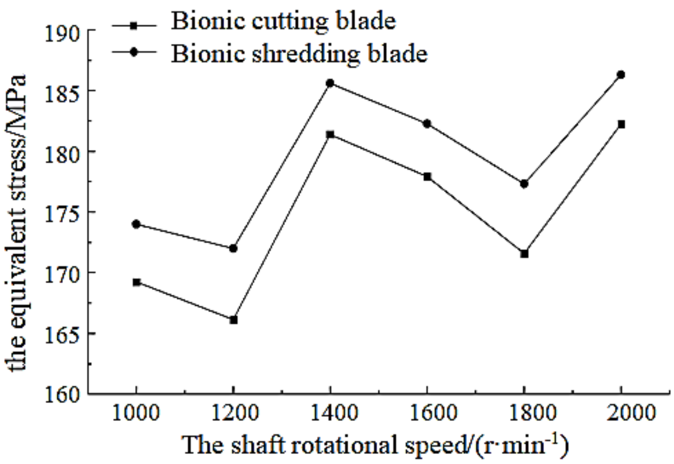


Fig. 9- The influence of spindle speed on test index

Effect of blade installation angle

As demonstrated in Figure 10, variations in the blade installation angle significantly impact the maximum equivalent stress during the straw cutting process. Initially, there is a gradual increase in this stress, followed by a subsequent decrease. The maximum equivalent stress rises from 167.23 MPa to 183.80 MPa, before diminishing to 175.05 MPa. The highest equivalent stress occurs at a blade installation angle of 55°. Additionally, when the angle of the biomimetic shredding knife is set to 50°, the equivalent stress on the corn stover peaks, reflecting a 9.17% increase compared to the maximum equivalent stress observed at a 70° angle.

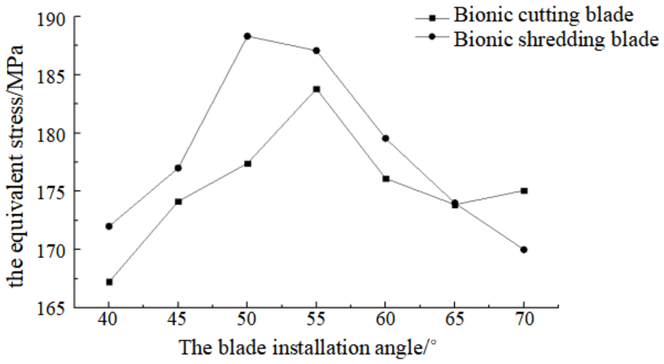


Fig. 10 -The influence of setting angle on test index

Effect of traveling speed

The effect of traveling speed on the maximum equivalent stress during the straw cutting process is shown in Figure 11. As the traveling speed increases, the maximum equivalent stress on the straw initially rises, then decreases, and subsequently shows an increasing trend again. When the cutting knife's travel speed is set at 2.5 km/h, the straw undergoes its peak equivalent stress, which is 4.50% greater than that at a speed of 1.5 km/h. Additionally, at a speed of 4.5 km/h, the bionic cutting knife subjects the straw to its highest equivalent stress. At a travel speed of 2.5 km/h, the stress is the second highest.

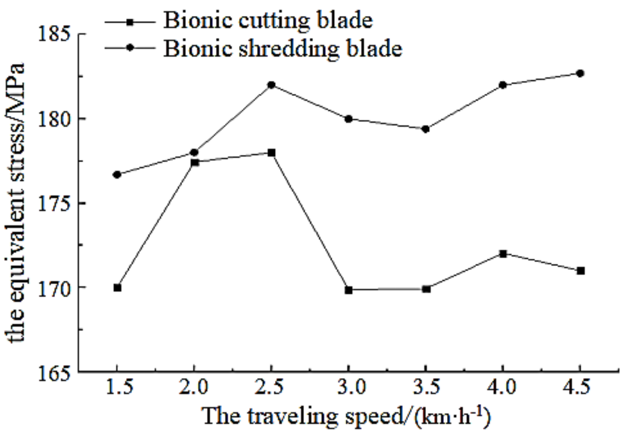


Fig. 11 - The influence of velocity on test index

Effect of blade tilt angle

Figure 12 presents the maximum equivalent stress endured by corn straw as the blade tilt angle changes from 0° to 30°. At a tilt angle of 0°, the maximum equivalent stress recorded for the cutting knife and shredding knife reaches its highest points, measuring 182.27 MPa and 188.78 MPa respectively. When comparing this to a tilt angle of 30°, the maximum equivalent stress values show an increase of 5.55% and 6.48%.

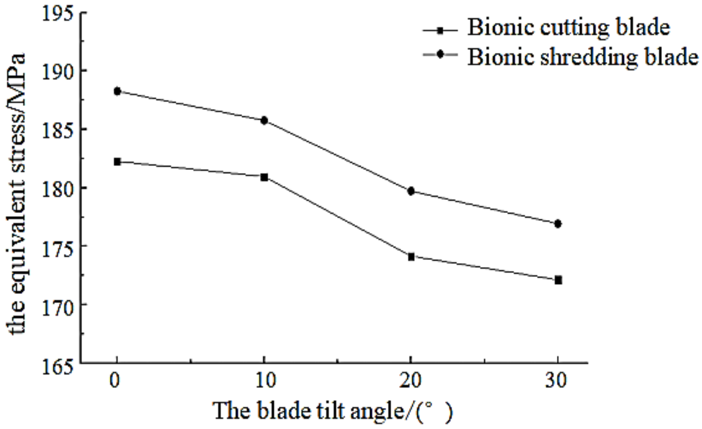


Fig. 12 - The influence of slant angle on test index

Multi-factor test

Based on the findings from the unifactorial experiment, the table coding the levels of factors has been generated and is displayed in Table 3. The protocols and findings are elaborated in Table 4.

Table 3

Table of factors and levels

Levels	Shaft rotational speed *A*[r/min]	Blade installation angle *B* [°]	Traveling speed *C* [km/h]	Blade tilt angle *D* [°]
1	1600	60	4.0	15
2	1500	55	3.5	10
3	1400	50	3	5
4	1300	45	2.5	0

Table 4

Orthogonal test plan and results

Test No.	*A*	*B*	*C*	*D*	Vacant column	Equivalent stress of cutting straw/MPa	Equivalent stress of shredding straw/MPa
1	1	1	1	1	1	176.71	174.96
2	1	2	2	2	2	181.25	179.29
3	1	3	3	3	3	178.13	184.58
4	1	4	4	4	4	174.15	180.03
5	2	1	2	3	4	179.57	179.38
6	2	2	1	4	3	186.14	187.88
7	2	3	4	1	2	174.81	183.21
8	2	4	3	2	1	177.07	184.83
9	3	1	3	4	2	181.23	183.12
10	3	2	4	3	1	186.02	182.84
11	3	3	1	2	4	185.50	190.17
12	3	4	2	1	3	179.70	185.96
13	4	1	4	2	3	176.19	175.22
14	4	2	3	1	4	183.21	178.65
15	4	3	2	4	1	182.81	188.14
16	4	4	1	3	2	180.24	188.26

Note: A, B, C, and D represent the horizontal values of the tool spindle speed, blade installation angle, travel speed, and blade tilt angle, respectively.

Analysis of variance for experimental results

A variance analysis was conducted on the test results. As illustrated in Table 5, when the cutting blade processes straw, the hierarchy of the impact of the test variables on the maximum equivalent stress experienced by the straw is ranked as follows: blade installation angle > shaft rotation speed > traveling speed > blade inclination angle.

Table 5

Variance analysis table of maximum equivalent stress on stalk under cutting blade

Sources	Squares	DF	MS	F value	P value	Significance
A	65.05	3	21.68	15.32	0.025	*
B	98.44	3	32.81	23.19	0.014	*
C	40.28	3	13.43	9.49	0.048	*
D	15.90	3	5.30	3.75	0.153	
Lake of Fit	4.245069	3	1.41502			

Note: *, significance level 0.01 < P < 0.05; **, significance level P < 0.01.

The variance analysis presented in Table 6 regarding the maximum equivalent stress experienced by straw when cut by the shredding knife illustrates that the predominant factors affecting this stress, in order of significance, are: blade installation angle, knife shaft rotation speed, traveling speed, and blade inclination angle.

Table 6

Variance analysis table of maximum equivalent stress on stalk under shredding blade

Sources	Squares	DF	MS	F value	P value	Significance
A	71.95	3	23.98	13.46	0.030	*
B	158.20	3	52.73	29.57	0.010	*
C	50.29	3	16.76	9.40	0.049	*
D	37.86	3	12.62	7.08	0.071	
Lake of Fit	5.35	3	1.78			

Note: *, significance level 0.01 < P < 0.05; **, significance level P < 0.01.

Intuitive analysis for experimental results

The analytical outcomes pertaining to the maximum equivalent stress experienced by corn straw when affected by the cutting knife and the shredding knife are presented in Tables 7 and 8. When utilizing the cutting knife, the hierarchy of factors affecting the maximum equivalent stress on straw is *B>A>C>D*. Specifically, this pertains to the cutting knife installation angle, knife shaft rotational speed, travel speed, and blade inclination angle. The optimal configuration within the tested parameter range is $A_3B_2C_1D_1$, corresponding to a knife shaft rotational speed of 1400 r/min, a cutting knife installation angle of 55°, a travel speed of 4.0 km/h, and a blade inclination angle of 0°. When utilizing the shredding knife, the arrangement of factors affecting the maximum equivalent stress on straw is prioritized as *B>A>C>D*. The most effective parameter combination identified within the experimental factor limits is $A_3B_3C_1D_4$, which corresponds to a knife shaft rotational speed of 1400 r/min, a blade installation angle of 50°, a travel speed of 4.0 km/h, and a blade inclination angle of 0°.

Table 7

Maximum equivalent stress on stalk under cutting blade

Index	*A*	*B*	*C*	*D*
Mean value 1	177.56	178.43	182.15	178.61
Mean value 1	179.40	184.16	180.83	180.01
Mean value 1	183.11	180.31	179.91	180.99
Mean value 1	180.61	177.79	177.79	181.08
Range	5.55	6.37	4.36	2.48
Primary and secondary factors	*B>A>C>D*			
Optimal configuration	$A_3B_2C_3D_4$			

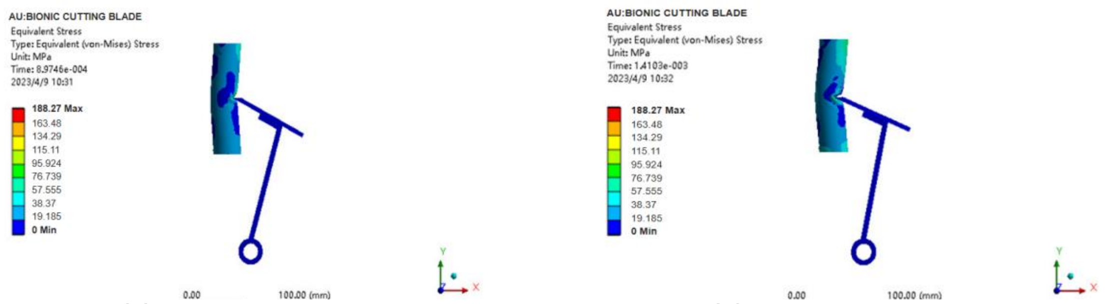
Table 8

Maximum equivalent stress on stalk under shredding blade

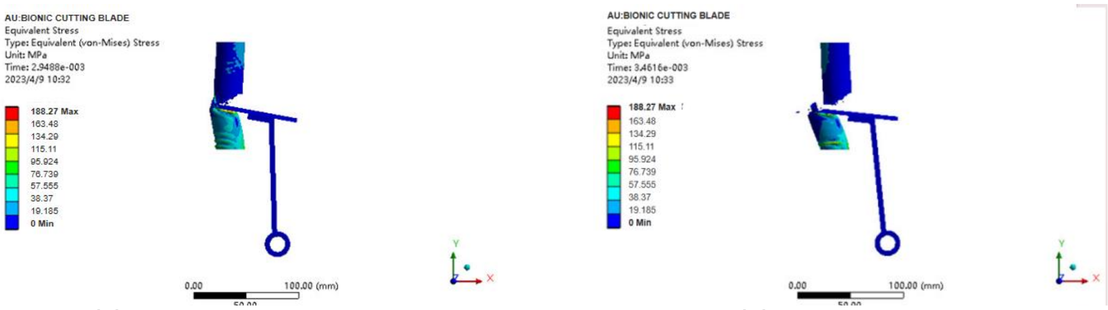
Index	*A*	*B*	*C*	*D*
Mean value 1	179.72	178.17	185.32	180.70
Mean value 1	183.83	182.17	183.19	182.38
Mean value 1	185.53	186.53	182.80	183.770
Mean value 1	182.57	184.77	180.33	184.79
Range	5.81	8.36	4.99	4.10
Primary and secondary factors	*B>A>C>D*			
Optimal configuration	$A_3B_3C_1D_4$			

Simulation of cutting corn straw with cutting blade and shredding blade

Figure 13 illustrates the procedure for severing straw utilizing the cutting blade.



(a) Initial cutting moment *(b) Preliminary cut-off phase*

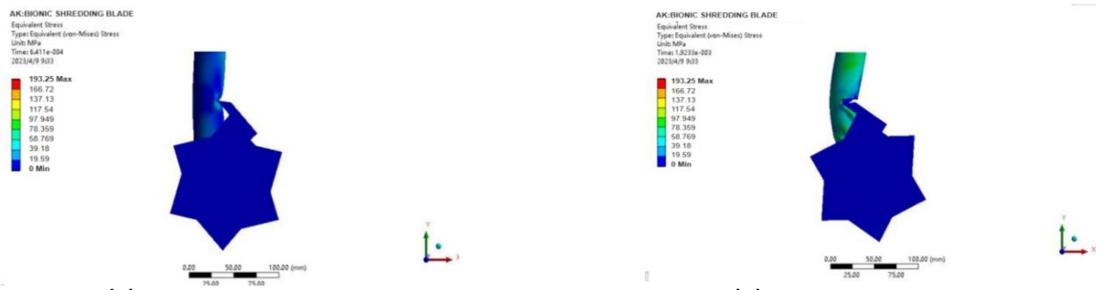


(c) Impending severance phase *(d) Final incision phase*

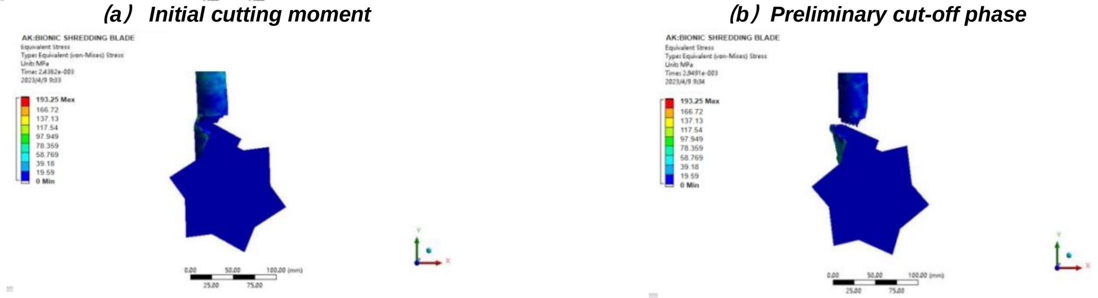
Fig. 13- Nephogram of equivalent stress of corn stalk during cutting process

Throughout the cutting procedure, the straw undergoes an initial compression, resulting in a progressive increase in the equivalent stress exerted on it. When this equivalent stress reaches a significant threshold, the cutting blade penetrates the straw, leading to substantial plastic deformation in the severed section. As the process advances, the equivalent stress on the straw decreases and fluctuates within a small range. Just before the straw is severed, the equivalent stress on the straw increases slightly. The maximum equivalent stress is localized at the severed section of the corn straw. Significant deformations are also observed in the upper and lower segments of the straw. During simulated cutting operations utilizing the bionic cutting knife, the peak equivalent stress recorded on the corn straw reaches 188.27 MPa.

Figure 14 illustrates the procedure for severing straw utilizing the shredding blade. The equivalent stress in corn straw is primarily localized at the point of incision. Additionally, the regions directly above and below the cut are subjected to variations in equivalent stress. During the corn straw cutting procedure, the straw is initially subjected to compression, resulting in a gradual increase in its equivalent stress. When this equivalent stress reaches its peak, the cutting blade penetrates the straw, leading to deformation in the section that has been severed. Following this, the equivalent stress begins to decrease and exhibits minor fluctuations until the conclusion of the cutting operation. The maximum recorded equivalent stress at the moment the cutting blade engages the corn straw is 193.25 MPa.



(a) Initial cutting moment *(b) Preliminary cut-off phase*



(c) Impending severance phase *(d) Final incision phase*

Fig. 14 - Nephogram of equivalent stress of corn stalk during cutting process

CONCLUSIONS

(1) This study presents the design of a longitudinal straw chopping apparatus for corn harvesters, alongside the development of a bionic blade for essential components. Furthermore, the force model in the horizontal direction during the extrusion phase of the primary cutting surface, as well as the force models relevant to both the primary and secondary cutting surfaces during the plastic deformation phase were established.

(2) A cutting model for a straw-bionic cutting knife has been developed using ANSYS-LYNA software. The model evaluates test factors including knife shaft rotational speed, blade installation angle, forward speed, and blade inclination angle through single-factor and four-factor, four-level orthogonal experiments. The primary evaluation metric is the maximum equivalent stress experienced by straw during the cutting operation of both bionic cutting and chopping knives. The findings indicate that the knife shaft rotational speed, cutting knife installation angle, and traveling speed exert significant influence on the maximum equivalent stress of straw, with the order of significance being blade installation angle > knife shaft rotational speed > traveling speed > blade inclination angle. The optimal parameters for the bionic cutting knife, within the tested factor range, are a knife shaft rotational speed of 1400 r/min, a blade installation angle of 55°, a traveling speed of 4.0 km/h, and a blade inclination angle of 0°. Conversely, the ideal parameter set for the bionic chopping knife is also a knife shaft rotational speed of 1400 r/min, a blade installation angle of 50°, a traveling speed of 4.0 km/h, and a blade inclination angle of 0°.

ACKNOWLEDGEMENT

This research was supported by the Natural Science Foundation of Liaoning Province (2024-BS-287), the "Enterprise Doctor Dual Innovation Plan" of Yingkou City (YKSCJH2023-015), and the scientific initiatives backed by Liaoning Agricultural Technical College (Lnz202216, Lnz202310).

REFERENCES

[1] Aygun, I., Cakir. E., (2014). Development and determination of the field performance of stalk choppers equipped with different blade configurations. *Bulgarian Journal of Agricultural Science*, Vol. 20, pp.1268-1271, Izmir/ Turkey.

[2] Chen B.., Chu X., Huang B., Liu Y., Ge Y., (2024). Simulation and experiment of potato excavator. *INMATEH-Agricultural Engineering*, Vol. 74, pp. 526-534, Bucharest / Romania.

[3] Gürkan Irsel., (2022). Strength-based design of a sunflower stalk cutter machine design using finite element analysis and experimental validation. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol.236, pp.1147-1168, Edirne/Turkey.

[4] Huang W., Ren D.Z., Gong YJ., Bai XW., Shi H., Liu C.W., (2021). Coupling Separation Simulation Analysis and Test of Corn Stalk Rind-pith Based on Abaqus (基于 Abaqus 的耦合式玉米秸秆皮穰分离仿真与试验). *Transactions of the Chinese Society of Agricultural Machinery*, Vol.52, pp.124-133, Shenyang/China.

[5] Huang WY., Qiu S., Ren D., Gong Y., Bai X., Wang W., (2021). Optimization of shearing parameters of corn stalks based on desirability function approach. *INMATEH-Agricultural Engineering,* Vol.64, pp.355-364, Bucharest / Romania.

[6] Li B., Chen Y., Chen J., (2016). Modeling of soil–claw interaction using the discrete element method (DEM). *Soil and Tillage Research,* Vol.158, pp.177–185, Yangling/China.

[7] Liu, P., Zhang Z., He J., Li H., Wang Q., Lu C., Lou S., Liu W., Cheng X. (2019). Kinematic analysis and experiment of corn straw spreading process. *INMATEH-Agricultural Engineering*, Vol. 58, pp. 83-92, Bucharest / Romania.

[8] Ren Z., Bai X., Li J., Gong Y., Gao Y., (2018). Design and Test on Roller-teeth Husking Roller in Rind-pith Separation of Corn Stalks (玉米秸秆皮瓤分离碾压揭皮辊设计与试验).*Transactions of the Chinese Society for Agricultural Machinery,* Vol.49, pp.93-99, Shenyang/China.

[9] Song Z., Song H., Yan Y., Li Y., Gao T., Li F., (2016). Optimizing design on knife section of reciprocating cutter bars for harvesting cotton stalk(棉花秸秆往复式切割器动刀片优化设计). *Transactions of the Chinese Society of Agricultural Engineering,* Vol.32, pp.42-49, Taian/China.

[10] Sun, J., Xing, K., Yang, Z., Duan J., (2022). Simulation and experimental research on fruit branch pruning process based on ANSYS/LS-DYNA (基于 ANSYS/LS-DYNA 的果枝修剪过程仿真与试验研究). *Journal of South China Agricultural University*, Vol.43, pp.113-124, Guangdong/China.

[11] Wan, J., Chen, W., Chen, C., Zheng, S., (2023). Analysis on power consumption model of hammer-JUNCAO mill system based on ANSYS Workbench/Ls-Dyna(基于 ANSYS Workbench/Ls-Dyna 的锤片－菌草粉碎系统的功耗模型分析). *Journal of Fujian Agriculture and Forestry University (Natural Science Edition)*, Vol. 52, pp.127-134, Fujian/China.

[12] Wu, K., Song, Y., (2022). Research Progress Analysis of Crop Stalk Cutting Theory and Method(农作物茎秆切割理论与方法研究进展分析). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.53, pp.1-20, Shandong/China.

[13] Xiao, W., Lu, J., Deng, C., (2022). Research on power consumption model of sugarcane harvester cutting system based on ANSYS/Ls-Dyna(基于 ANSYS/Ls-Dyna 的甘蔗收获机切割系统功耗模型研究). *Journal of Chinese Agricultural Mechanization,* Vol.43, pp.116-121, Nanning/China.

[14] Zhang, K., Zhang, W., Ma, J., Teng, S., (2021). Design and Experiment of Chopping Device for Corn Silage Test Bed (玉米青贮饲料试验台切碎装置设计与试验). *Forestry Machinery & Woodworking Equipment*, Vol.49, pp. 25-31, Gansu/China.

[15] Zhang, Y., Diao, P., Du, R., Liu, L., Zhang, J., (2016). Design and Test of Stalk Chopping and Conveying Device for Corn Combine Reaping both Stalk and Spike (穗茎兼收型玉米收获机茎秆切碎与输送装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol.47, pp. 208-214, Zibo/China.