OPTIMIZATION AND EXPERIMENT OF CUTTING PARAMETERS OF ALFALFA DISC-TYPE MOWER
/
圆盘式苜蓿切割器参数优化与试验

Yong YOU*), Pengzhan HU, Lu ZHU, Haiyi WANG, Yunting HUI, Decheng WANG
China Agricultural University, College of Engineering, Beijing / China
Tel: +86 10 010-62737977; +86 10 010-62737208; E-mail: youyong@cau.edu.cn;
Corresponding author: Yong You;
DOI: https://doi.org/10.35633/inmateh-73-10

Keywords: *forage, alfalfa harvesting, disc-type cutter, mower, low-loss cutting*

ABSTRACT
Optimization and experimental research on the cutting parameters of the cutter were carried out to solve the high re-cutting rate and loss rate under high-speed harvesting of alfalfa disc-type cutter. Kinematics theory was used to analyze the movement trajectory and cutting area of the cutter in the cutting process, and theoretical calculations to carry out an analysis of the factors affecting the re-cutting area of the cutter. A working parameters adjustable cutting test bench was designed and produced, and cutting experiments of alfalfa were conducted using this test bench combined with response surface methodology. The optimized factors combination was solved by quadratic fitting function, and the value of cutterhead diameter, blade twist angle, and cutting inclination angle was 407.04 mm, 4.21°, and 4.51°, respectively. The verification test showed that the average re-cutting rate and loss rate were 1.48% and 3.13%, less than national standard requirements for alfalfa harvesting quality (re-cutting rate <1.5%; loss rate <4%), low-loss cutting of alfalfa was achieved, and the harvesting quality of the disc-type cutter was improved.

摘要
针对圆盘式苜蓿切割器高速收获下重割率及损失率高的问题，开展了切割器切割参数优化与试验研究。运用运动学理论分析了割刀切割过程中的运动轨迹及切割区域，通过理论计算进行了切割器重割面积影响因素分析。设计并搭建了一款作业参数可调切割试验台架，结合响应曲面试验方法，利用切割试验台架开展苜蓿田间收割试验。利用二次拟合方程求得最优参数组合为刀盘直径 407.04 mm、割刀扭转角 4.21°、切割倾角为 4.51°。验证试验结果表明，最优参数组合下平均损失率为 3.13%、平均重割率为 1.48%，小于苜蓿收获质量的国家标准要求（损失率＜4％；重割率＜1.5％），实现了苜蓿的低损失切割，提升了圆盘式切割器高速收获下的作业质量。

INTRODUCTION
With the introduction of policies such as national planting structure adjustment, "grain to fodder" and returning farmland to grass, the planting area of forage grass in China has further increased *(Chen et al., 2015; Jiang et al., 2016; Li et al., 2020; Zhu et al., 2022; Wang et al., 2017; Guo et al., 2019)*. Forage industry development cannot be separated from the support of machinery and equipment, disc mowers with high efficiency, and no vibration characteristics, in modern mower products have a wide range of applications *(Fu et al., 2018; Zhao et al., 2014; Hou et al., 2020; Xie et al., 2020; Vasiliev N. et al., 2021; Otroshko S. et al., 2021)*. Disc-type forage cutter still has the problem of high re-cutting rate and loss rate under high-speed harvesting at this stage, which limits the development of the forage industry.

Aiming at efficient and low-loss crop harvesting, there have been many related researches, domestically and abroad. Song et al. *(2020)* prepared a self-sharpening cutter with a metal-ceramic gradient to achieve low-damage cutting of alfalfa by maintaining the cutting performance of the cutter during harvesting. *Du et al (2022)* designed a bionic blade for a single-row tea harvester based on the curved structure of cricket incisors according to the bionic principle, which reduces the tea-cutting resistance and power consumption. *Hao et al, (2018),* found that different shapes of cutting blades had a significant effect on the energy consumption of the equipment and field performance during the harvesting of manzanita. *Shi et al, (2017),* optimized the parameters such as cutting speed, cutting inclination angle, and a working speed of an orderly harvester for artemisia by orthogonal tests to improve the cutting performance of the harvester. *Fu (2014)* and *Wu (2017)* determined the optimum region for the blade twist angle and the cutting inclination angle based on the complex vector theory. *Johnson Phillip C. et al (2012)* designed a pendulum cutting mechanism for the cutting of mango grass stalks, and the study showed that the energy required for cutting is directly proportional to the cutting speed, and there exists the optimum cutting bevel angle so that the cutting consumes the least amount of energy. *Zhang et al (2019)* studied the optimum blade slant cutting angle for rice stalks under-supported and unsupported cutting to provide a reference for the height adjustment of the rice harvester cutting table. *Hou et al, (2020),* analyzed the effect of different blade angles and slant cutting angles of disc cutter knives on the cutting quality of castor beans to obtain optimum operating parameters through experimentation. *Chandra Gupta, (1992),* designed a rotary single-disc sugarcane cutter test bench, and the optimal operating parameters of the single-disc sugarcane cutter were obtained through computerized acquisition of the mechanical power and cutting torque of the cutter. In summary, relevant scholars mainly aim at reducing the crop-cutting power consumption and improving the operational performance of cutting machine tools at present, and have conducted research around the design of crop stalk cutting tools and optimization of cutting parameters by methods such as computer simulation and analysis or cutting test platform, and have achieved certain results. However, the disc-type forage cutter is prone to produce multiple cutting areas under high-speed harvesting, repeated cutting of forage and stubble, leading to the phenomenon of uneven stubble height, which affects the yield of perennial forage such as alfalfa and the quality of the next round of growth. Therefore, it is of great significance to carry out the theoretical analysis of the cutting system of the disc-type cutter and the influence factors of re-cutting, and to research on the matching relationship of the cutting parameters to improve the harvesting quality of the mower during high-speed harvesting.

This paper carries out theoretical research on disc-cutting systems according to the kinematics principle, and explores the relationship between the re-cutting area and cutting parameters. A parameter adjustable cutting test bench is constructed, and key cutting parameters are optimized by response surface test to reduce the cutting loss rate and re-cutting rate, the harvesting quality of the cutter at high-speed harvesting is improved.

MATERIALS AND METHODS

Theoretical analysis of cutting systems

- **Cutting kinematics analysis**

The disc-type cutter adopts the unsupported cutting method to cut the alfalfa, suitable cutting speed is the first condition for successful completion of the cutting action. In addition, the mower cutting system often adopts two special structures twisting cutter and tilting disc. Tilting the cutterhead at an angle to the ground can reduce the stubble height and improves the cutting quality of the alfalfa; at the same time, make the cutting mode from cross-cutting to oblique cutting, reduce the cutting resistance and power consumption *(Li, 2014; Dong, 2020)*. Blade twisted at a certain angle can make the back of the knife produce an upward thrust to the stalks after the stalks were cut off, reducing the re-cutting phenomenon and cutting losses.

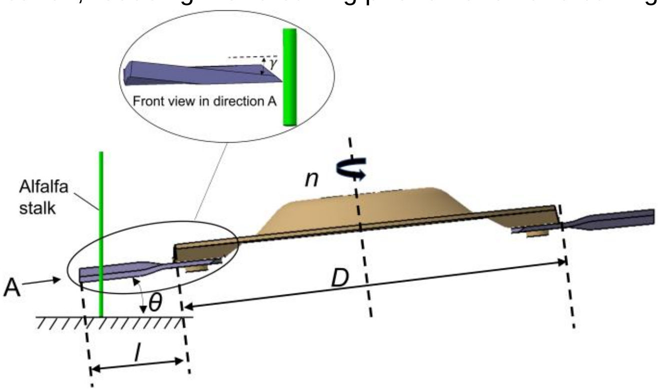


Fig. 1 - Working principle diagram

Note: n is the rotation speed of the cutterhead; D is the cutterhead diameter; l is the blade length that extends out of the cutterhead; γ is the blade twist angle; θ is the cutting inclination angle

To determine the movement trajectory of the blade and the cutting area, the kinematical cutting process of the disc mower is analyzed. The cutterhead mainly consists of the left and right cutter discs, as shown in Fig. 2 and Fig. 3. *A*, *B* and C, D are points in the same position of blades 1, 2, and 3, 4, respectively. The center *O* of the disc circle is the basis for the establishment of a coordinate system, the equation of motion of the points *A*, *B*, *C*, and *D* is:

$$\begin{cases} x_{oA} = 2r + l_1 + (\Delta l + r)\cos\phi \\ y_{oA} = (\Delta l + r)\sin\phi + v_m t \end{cases} \quad (1)$$

$$\begin{cases} x_{oB} = 2r + l_1 + (l + r)\cos\phi \\ y_{oB} = (l + r)\sin\phi + v_m t \end{cases} \quad (2)$$

$$\begin{cases} x_{oC} = (\Delta l + r)\sin\phi \\ y_{oC} = (\Delta l + r)\cos\phi - v_m t \end{cases} \quad (3)$$

$$\begin{cases} x_{oD} = (l + r)\sin\phi \\ y_{oD} = (l + r)\cos\phi - v_m t \end{cases} \quad (4)$$

Where: r is the cutterhead diameter, (mm);

l is the blade length extending out of the slide palm, (mm);

l_0 is the length of the blades, (mm);

l_1 is the cutterhead spacing, (mm);

Δl is the difference between the 'l' and 'l_0', (mm);

v_m is the speed of the tractor, (m/s);

Φ is the blade rotated angle relative to initial position, (°);

According to the trajectory equations, the movement trajectories of the points on the blade and the composed cutting area are plotted in Fig. 2. Curves 1A and 2A represent the movement trajectories of point *A* on blades 1 and 2, respectively, and curve 3A represents the movement trajectory of point A on blade 1 after the cutterhead is rotated by an angle of 2π; The rest of the points on the cutterhead have a same motion trajectory rule to A.

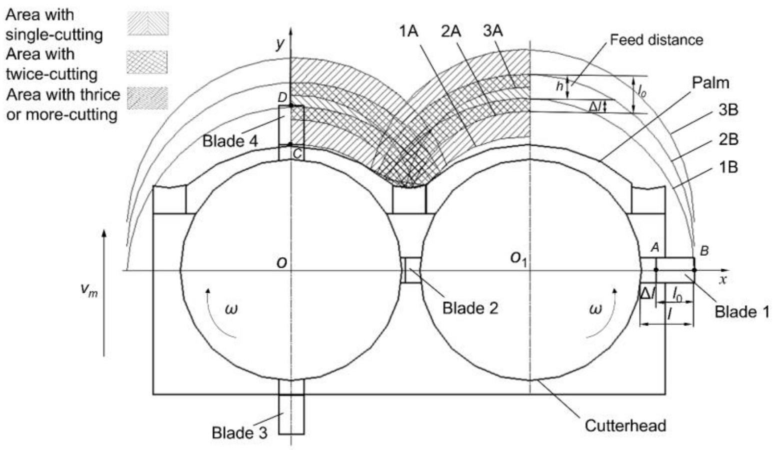


Fig. 2 - Cutting area diagram of disc cutter

h is the feed distance of the cutter, mm; O is the coordinate origin (the center of the left cutterhead circle); O_1 is the circle center of the right cutterhead.

During the cutting process, the trajectory equation of blade 2 lags π phases behind blade 1, and the trajectory equation of blade 3 lags π phases behind blade 4. According to the above motion equations, the absolute motion trajectory equations of each point on the blade are further introduced.

$$y_{2A} = (\Delta l + r)\sin[arccos(\frac{x-2r-l_1}{\Delta l+r})] + \frac{v_m}{\omega}[arccos(\frac{x-2r-l_1}{\Delta l+r}) + \pi] \quad (5)$$

$$y_{1B} = (l + r)\cos[arcsin(\frac{x}{l+r})] + \frac{v_m}{\omega}arcsin(\frac{x}{l+r}) \quad (6)$$

$$y_{2C} = (\Delta l + r)\cos[arcsin(\frac{x}{\Delta l+r})] + \frac{v_m}{\omega}[arcsin(\frac{x}{\Delta l+r}) + \pi] \quad (7)$$

$$y_{1D} = (l + r)\cos[arcsin(\frac{x}{l+r})] + \frac{v_m}{\omega}arcsin(\frac{x}{l+r}) \quad (8)$$

where: ω is the angular velocity of the blade, (rad/s);

- **Theoretical analysis of factors influencing re-cutting area**

The cutting trajectory of the cutter blade is related to the forward speed v_m of the tractor, the angular velocity ω of the cutterhead, the length l of the cutterhead, and the radius r of the cutterhead. As shown in Fig. 3, in determining the theoretical length of the cutter blade extending out of the cutterhead, there is a reduction of the re-cutting area and the top of the cutterhead does not produce a missed cut. Therefore, to reduce the re-cutting area and avoid missed cuts at the top of neighboring blades, it is necessary to ensure that the feed distance h is equal to the length of the blade l_0, which is determined by the forward speed v_m of the tractor and the angular velocity ω of the cutterhead together.

$$y_B = v_m\frac{\pi}{2\omega} + R \quad (9)$$

$$y_A = v_m\frac{\frac{\pi}{2}+\alpha}{\omega} + r_1 \quad (10)$$

where: y_B is the tractor moves forward distance after the blade turning at π/2 angle, (mm);
y_A is the tractor moves forward distance after the blade turning at (π/2+α) angle, (mm);
R is the distance from the blade top to the cutterhead center, (mm);
r_1 is the distance from the blade root to the cutterhead center, (mm);
$α$ is the angle between adjacent blades, take π;
Let y_B=y_A, i.e.

$$\frac{v_m\pi}{2\omega}+R=v_m\frac{\frac{\pi}{2}+\alpha}{\omega}+r_1 \tag{11}$$

$$R-r_1=l_0=\frac{v_m\alpha}{\omega} \tag{12}$$

The relationship between the radius r and the re-cutting area was analyzed to obtain the velocity equations of the points on the cutter, take the first derivatives of the motion equations of the points at the root and the top of the blade. To achieve alfalfa cutting successfully, the linear velocity of the blade root must be faster than the minimum velocity of unsupported cutting of alfalfa $v_{\min}$. Taking point C as an example, its velocity equation is shown in Equation (13), and according to the velocity synthesis theorem, the absolute velocity of point C is shown in Equation (14).

$$\begin{cases} v_{xC}=(\Delta l+r)\omega\cos\phi \\ v_{yC}=-(\Delta l+r)\omega\sin\phi-v_m \end{cases} \tag{13}$$

$$v_C=\sqrt{{v_{xC}}^2+{v_{yC}}^2}=\sqrt{(\Delta l+r)^2\omega^2-2v_m(\Delta l+r)\omega\sin\phi+{v_m}^2} \tag{14}$$

The angle Φ is π/2 when point C is rotated to the horizontal position, point C has the minimum absolute velocity at this time. For a determined blade length l_0 and cutterhead angular velocity ω, i.e.:

$$r\geq\frac{v_m+v_{min}}{\omega} \tag{15}$$

At the determined forward speed of the tractor, the angular velocity of the cutterhead, and the blade length, the trajectory equation of the cutterhead was integrated, and the cutting area as a function of the cutterhead radius was obtained, as shown in Fig. 3. Due to the complexity of solving the intersection of the blade trajectory, it is difficult to directly solve all the re-cutting area. To represent the relationship between the cutterhead radius and the re-cutting area intuitively, take two identical intervals between the cutterhead center and the edge of the cutterhead, the area between the two curves under different cutterhead radius r was calculated.

$$S_1=\int_{-20}^{0}(y_{1D}-y_{2C})dx \tag{16}$$

$$S_2=\int_{-r}^{-r+20}(y_{1D}-y_{2C})dx \tag{17}$$

$$S_i=\frac{S_1}{S_2},\quad \left(r\geq\frac{v_m+v_{min}}{\omega}-\Delta l\right) \tag{18}$$

where: S_1 is the area between y_{1D} and y_{2C} on the interval [-20, 0] mm, (mm²);
S_2 is the area between y_{1D} and y_{2C} on the interval [-r, -r+20] mm, (mm²).

$$Y_{2C}=\int y_{2C}\ \mathrm{d}x=\frac{(\Delta l+r)^2\arcsin(\frac{x}{\Delta l+r})}{2}+xr\arcsin(\frac{x}{\Delta l+r})+\frac{x\sqrt{(\Delta l+r)^2-x^2}}{2}+\frac{v_m(\Delta l+r)}{\omega}\sqrt{1-(\frac{x}{\Delta l+r})^2}+\frac{\pi v_m x}{\omega} \tag{19}$$

$$Y_{1D}=\int y_{1D}\ \mathrm{d}x=\frac{(l+r)^2\arcsin(\frac{x}{l+r})}{2}+xr\arcsin(\frac{x}{l+r})+\frac{x\sqrt{(l+r)^2-x^2}}{2}+\frac{v_m(l+r)}{\omega}\sqrt{1-(\frac{x}{l+r})^2} \tag{20}$$

The relationship between cutterhead radius and re-cutting area under different tractor speeds and cutterhead angular velocity is shown in Fig. 4. The re-cutting area is positively correlated with the cutter feed distance, and small feed distance can reduce the re-cutting area of the cutterhead, but the slower tractor speed, and faster cutterhead angular velocity will increase the power consumption; in the determined feed distance, the re-cutting area is positively correlated with the cutterhead radius, and the reduction of the radius can reduce the re-cutting area of both two sides of the cutterhead, and the cutting effect will be improved.

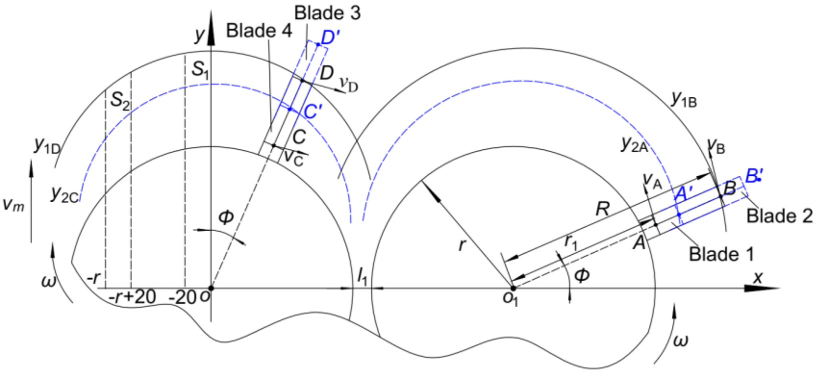


Fig. 3 - Motion parameters diagram of blade

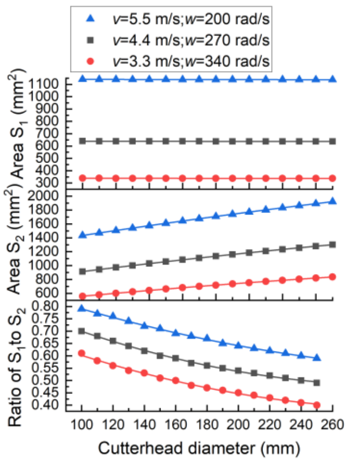


Fig. 4 - Relationship between cutter radius and re-cutting area

Response surface Box-Behnken experiment

- **Experiment equipment and materials**

A cutting test bench was built to explore the influence on the cutting effect of the cutting parameters. The test bench mainly consists of a suspension frame, transmission system, lifting components, and cutterhead assembly, as shown in Fig. 5.

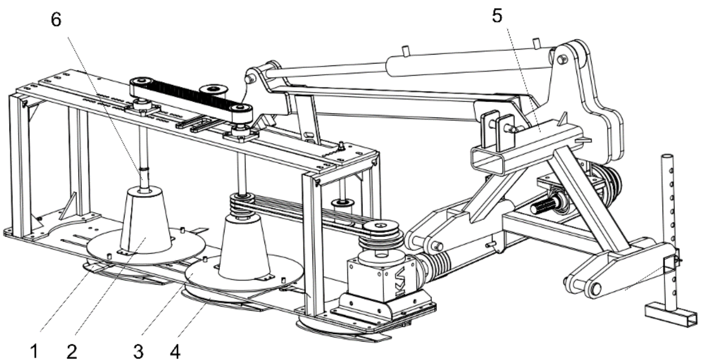


Fig. 5 - Structure diagram of cutting test bench

1 - blade; 2 - drum; 3 - cutterhead; 4 – slide palm; 5 - suspension frame; 6 - cutterhead mounting shaft

A response surface experiment was carried out by using the cutting test bench to optimize the cutting parameters of the disc cutter. The experiment was conducted in October 2022 at the alfalfa planting test field of the National Forage Industry Technology System of Qingdao Agricultural University, (Jiaozhou, Qingdao, Shandong Province, China). The surface of the field was levelled, and the alfalfa cultivar was 'Zhongmu No. 3'. The alfalfa was in the late bud stage and early flowering stage during the experiment, with good growth and no collapse phenomenon. The height of alfalfa plants was measured to be about 400~600 mm.

- **Experimental factors and levels**

Three experiment factors were selected: cutterhead diameter X_1, blade twist angle X_2, and cutting inclination angle X_3. The cutterhead rotation speed of 2640 r/min and tractor speed of 4.4 m/s were determined through the pre-test before carrying out the Box-Behnken test, three factor levels are the cutterhead diameter of 350-480 mm, the blade twist angle of 0-8 °, the cutting inclination angle of 0-8 °, respectively. The factor level codes are shown in Table 1.

Table 1

Coding of factor levels

Level	Cutterhead diameter X_1 (mm)	Blade twist angle X_2 (°)	Cutting inclination angle X_3 (°)
-1	350	0	0
0	415	4	4
1	480	8	8

- **Experimental indicators**

The test indicators were selected as loss rate Y_1 and re-cutting rate Y_2, each test indicator was calculated as follows:

(1) loss rate

The total loss rate for harvesting is calculated according to Equation (21):

$$S = S_z + S_l \tag{21}$$

where: S is the total harvest loss rate;

S_z is overcutting loss rate (the ratio of the stubble mass overcutting to stubble mass required left);

S_l is missed cutting loss rate (the ratio of the stubble mass missed cutting to stubble mass required left);

(2) re-cutting rate

The re-cutting rate is the ratio of the mass of headless nodes per unit area to the mass of alfalfa to be harvested, it is calculated according to Equation (22):

$$S_e = \frac{g_w}{g_z} \tag{22}$$

where: S_e is the re-cutting rate;

g_w is the actual mass of headless grass nodes harvested per unit area, g/m^2;

g_z is the total mass of harvested alfalfa per unit area, g/m^2;

Measurements of operational indicators at the test site are shown in Fig. 6:

a) ***b)***

Fig. 6 - Situation of experimental field

a) cutting parameter adjustment; b) working process

RESULTS

Experimental results

Based on the Box-Behnken quadratic regression orthogonal test design scheme, including 17 test points, including 12 analytical factors and 5 zero estimation errors, the test scheme and test results are shown in Table 2.

Table 2

Quadratic regression orthogonal response surface test results

Experimental number	X_1	X_2	X_3	Loss rate Y_1/%	Re-cutting rate Y_2/%
1	350	4	8	3.63	1.32
2	350	0	4	3.89	1.51
3	350	8	4	3.84	1.26
4	350	4	0	3.76	1.46
5	415	4	4	3.08	1.41
6	415	4	4	3.05	1.4
7	415	0	8	3.79	1.49
8	415	4	4	3.09	1.43
9	415	8	0	3.85	1.54
10	415	8	8	3.72	1.34
11	415	0	0	3.93	1.71
12	415	4	4	3.09	1.45
13	415	4	4	3.1	1.42
14	480	4	0	3.94	1.7
15	480	8	4	4	1.47
16	480	4	8	3.8	1.49
17	480	0	4	4.26	1.57

- **Regression model**

According to the sample data in Table 2, the analysis of variance of the quadratic regression equation of the loss rate Y_1 and re-cutting rate Y_2 on three factors was established through Design-Expert 13 software, and the results are shown in Table 3.

Table 3

Analysis of variance of experimental results

Source	Loss rate				Re-cutting rate			
	Squares	DF	F value	P value	Squares	DF	F value	P value
Models	2.45	9	218.55	<0.001**	0.2	9	36.71	<0.0001**
X_1	0.0968	1	77.62	<0.001**	0.06	1	86.92	<0.0001**
X_2	0.0264	1	21.21	0.002**	0.0561	1	84.38	<0.0001**
X_3	0.0364	1	29.23	0.001**	0.0741	1	111.45	<0.0001**
X_1X_2	0.011	1	8.84	0.0207*	0.0056	1	8.46	0.0227*
X_1X_3	0	1	0.02	0.8914	0.0012	1	1.84	0.2168
X_2X_3	0	1	0.02	0.8914	0.0001	1	0.1504	0.7097
X_1^2	0.8068	1	646.95	<0.001**	0.0001	1	0.0142	0.9083
X_2^2	0.961	1	770.59	<0.001**	0.0035	1	5.32	0.0544
X_3^2	0.2907	1	233.08	<0.001**	0.02	1	30.14	0.0009**
Lack of Fit	0.0072	3	6.53	0.0507	0.0032	3	2.86	0.1681
Pure Error	0.0015	4			0.0015	4		
Cor Total	2.46	16			0.2244	16		

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

The P-values of the response surface models for loss rate Y_1 and re-cutting rate Y_2 are less than 0.001 from the analysis in Table 3, indicating that the regression models are highly significant and statistically significant; the P-values of the lack of fit terms are all greater than 0.05, indicating that the regression equations are well fitted: their coefficients of determination, R^2, are 0.9965 and 0.9793, respectively, indicating that more than 95% of the response values can be explained by these 2 models. Therefore, the model can be used to optimize the cutting parameters.

The magnitude of the P-value of each parameter reflects its role in influencing the regression equation. The model insignificant regression terms were removed and the loss rate Y_1 and re-cutting rate Y_2 models were optimized as follow:

$$Y_1 = 3.08 + 0.11X_1 - 0.058X_2 - 0.068X_3 - 0.053X_1X_2 + 0.438{X_1}^2 + 0.478{X_2}^2 + 0.263{X_3}^2 \quad (23)$$

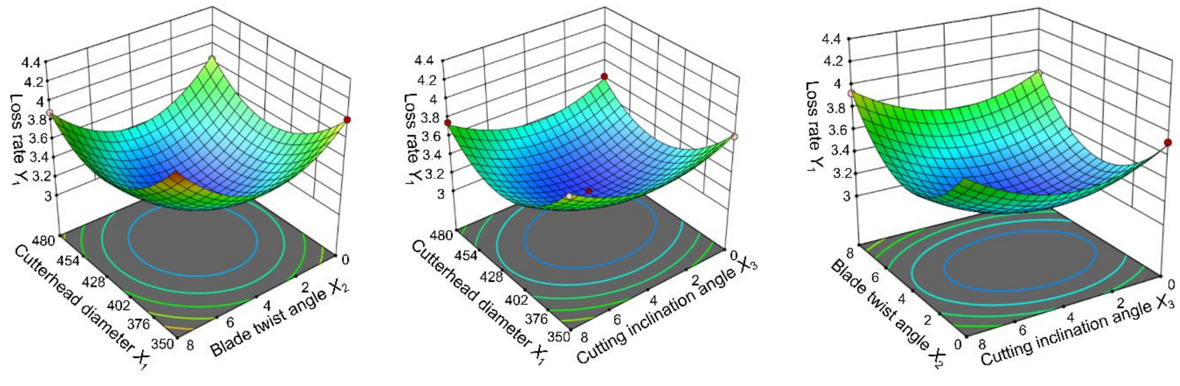
$$Y_2 = 1.44 + 0.085X_1 - 0.084X_2 - 0.096X_3 - 0.038X_1X_2 + 0.070{X_3}^2 \quad (24)$$

Based on the results of the regression equation analysis, the response surface was plotted using Design Expert software.

- **Analysis of the influence of interaction factors on cutting effect**

From the response graph of the influence of each factor on the loss rate Y_1, it can be learned that the change rule of the response surface is consistent with the results of the ANOVA of the regression equation and the model, and the overall trend of the influence of the cutterhead diameter X_1, the blade twist angle X_2 and the cutting inclination angle X_3 are moderate, the loss rate Y_1 is small. The main reason is that the cutterhead diameter affects the linear velocity; if the linear velocity is too small or too large, it will cause cutting loss; similarly, the cutter blade twist angle X_2 and cutting inclination angle X_3 determine the movement state of alfalfa after being cut and the cutting inclination angle, the three should be moderate to ensure the lower loss rate of harvesting.

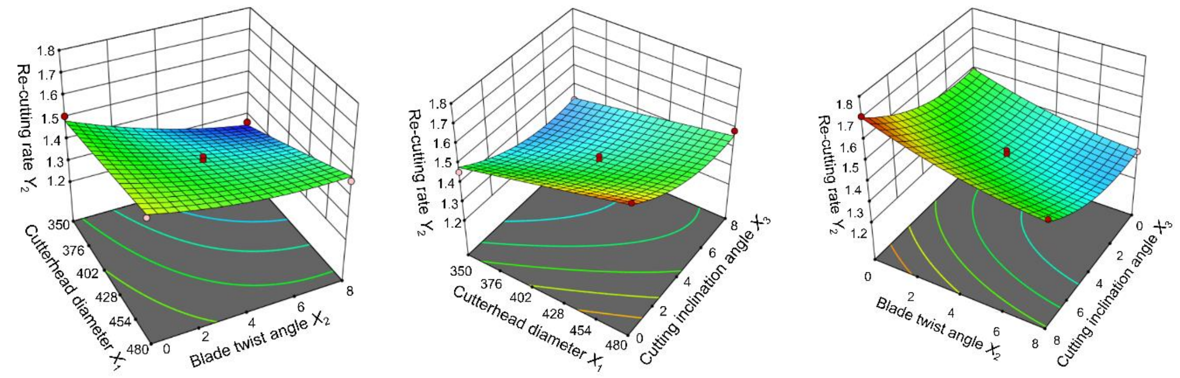
From the factors on the re-cutting rate Y_2 response graph can be learned, the change rule of the response surface and the regression equation analysis of variance results and the model is consistent, the overall impact of the trend for the smaller the cutterhead diameter, the larger the cutterhead twist angle, and the larger the cutting inclination angle X_3, the smaller the re-cutting rate Y_2. The main reasons are: when the cutterhead diameter is bigger, the cutterhead linear velocity is bigger, and the linear velocity is too big to cause excessive cutting and leaf loss; the bigger the blade twist angle is, the better the effect of the cutting inclination angle is on the lifting of the stalks, and avoiding the stalks from being cut repeatedly by the cutterhead; and the bigger cutting inclination angle is benefit for the alfalfa's feeding and flow.



a) *b)* *c)*

Fig. 7 - Response surface for double factors and loss rate

a) X_1 and X_2 interaction; b) X_1 and X_3 interaction; c) X_2 and X_3 interaction



a) *b)* *c)*

Fig. 8 - Response surface for double factors and re-cutting rate

a) X_1 and X_2 interaction; b) X_1 and X_3 interaction; c) X_2 and X_3 interaction

- **Parameter optimization and verification experiments**

To reduce the loss rate and re-cutting rate, the alfalfa harvesting standards (minimum loss rate and re-cutting rate ≤1.5%) were taken as the parameter optimization conditions, and the optimal parameter combinations were solved by using the Design-Expert software; the solution methods were as follows:

Objective function:
$$\begin{cases} f = min\, Y_1 \\ f = Y_2 \le 1.5\% \end{cases} \tag{25}$$

Boundary constraint function:
$$\begin{cases} 350 \le X_1 \le 480 \\ 0 \le X_2 \le 8 \\ 0 \le X_3 \le 8 \end{cases} \tag{26}$$

Design-Expert software was used to solve the optimization of each parameter. The optimal parameter combinations were obtained as cutterhead diameter (X_1) 407.04 mm, blade twist angle (X_2) 4.21°, and cutting inclination angle (X_3) 4.51°, which resulted in a loss rate of 3.07% and a re-cutting rate of 1.40%.

Verification test

To verify the optimal parameter combinations solved by the software, the verification test was carried out, and the test was repeated three times. Considering the rationality of mechanical structure and the convenience of measurement, the cutterhead diameter was set to 407 mm, the blade twist angle was set to 4°, and the cutting inclination angle was 4.5°. The results of the validation test are shown in Fig. 9, the alfalfa stubble is cut flush, the stubble height is following the standard, and the phenomenon of re-cutting and missed cutting is less.

a) *b)*

Fig. 9 - Verification test effect

a) mowed alfalfa *b) alfalfa stubble*

The results of the verification test are shown in Table 4. They show that under the optimal parameter combination, the average value of the loss rate is 3.13% (with a difference of 0.06% from the software solution value), less than national standard requirements for alfalfa harvesting re-cutting rate (1.5%), the standard deviation is 7.72%, and the coefficient of variation is 2.47%; the average value of the re-cutting rate is 1.48% (with a difference of 0.08% from the software solution value), less than national standard requirements for alfalfa harvesting loss rate (4%), the standard deviation is 15%, and the coefficient of variation is 10.14%; the harvesting effect is ideal, and optimization effect is obvious.

Table 4

Results of verification test

Experimental indicators	1	2	3	S.D.	C.V.
Loss rate Y_1(%)	3.21	3.10	3.08	7.72	2.47
Re-cutting rate Y_2(%)	1.40	1.46	1.59	15	10.14

CONCLUSIONS

(1) The theoretical study of the disc-type cutting system was carried out, the cutting area of the cutter was analyzed and mapped by kinematics theory, and the effects of feed distance and cutterhead radius on the re-cutting area of the cutter under high-speed harvesting were studied.

(2) A set of parametrically adjustable cutting test bench was built, and alfalfa field high-speed harvesting tests were conducted using the test bench. The test results showed that the order of significance of the factors affecting the loss rate was cutterhead diameter, cutting inclination angle, and blade twist angle, the effect of each factor on the re-cutting rate was highly significant.

(3) The optimal parameter combination of the disc cutter under high-speed harvesting was 407.04 mm for the cutterhead diameter, 4.21° for the blade twist angle, and 4.51° for the cutting inclination angle; the verification test showed that the average value of the loss rate under the optimal parameter combination was 3.13% and the average value of the re-cutting rate was 1.48%, which achieved the low-loss cutting effect under high-speed harvesting of the disc-type cutter.

ACKNOWLEDGEMENT

This work was supported by “Shandong Province Science and Technology-based Small and Medium-sized Enterprises Innovation Capacity Enhancement Project (2022TSGC2508) and China Forage and Grass Research System (CARS-34-21)”

REFERENCES

[1] Chen, L., Yu, Z., Mao, P., Sun, H., (2015), Development situation of forage grass industry and current status of forage quality safety in China(中国饲草产业发展概况及饲草料质量安全现状). *Feed Industry*, vol. 36, no. 5, pp: 56-60, Jilin/China.

[2] Chandra, P.G., Moses, F.O., (1992), Design of the Revolving Knife-type Sugarcane Base cutter. *Transactions of the ASABE*, vol. 35, no. 6, pp:1747-1752, United States.

[3] Du, Z., Li, D., Ji, J., Zhang, L., Li, X., Wang, H., (2022), Bionic Optimization Design and Experiment of Reciprocating Cutting System on Single-Row Tea Harvester. *Agronomy (Basel)*, vol. 12, no. 6, pp: 1309, Switzerland

[4] Dong, R., (2020), *Simulation and Experimental Study on Cutting Process of Silage Corn Harvesting Header (青贮玉米收获割台切割过程仿真及试验研究)*, MSc Thesis, Jilin University, Jilin/China.
[5] Fu, Z., (2014), *Study on Cutting System for Two Discs Mower Conditioner (双圆盘式刈割压扁机切割系统研究),* PhD Thesis, China Agricultural University, Beijing/China.
[6] Fu, Z., Wang, D., Li, W., Huang, Y., (2018), Design and Experiment of Two-disc Rotary Mower of Alfalfa (双圆盘式苜蓿旋转切割器设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, vol. 49, pp: 214-220, Beijing/China.
[7] Guo, T., Xue, B., Bai, J., Sun, Q., (2019), Discussion of the present situation of China's forage grass industry development: An example using alfalfa and oats (刍议中国牧草产业发展现状—以苜蓿、燕麦为例). *Pratacultural Science*, vol. 36, no. 5 pp: 1466-1474, Gansu/China.
[8] Gan, H., Mathanker, S., Momin, A., Kuhns, B., Stoffel, N., Hansen, A., Grift, T., (2018), Effects of three cutting blade designs on energy consumption during mowing-conditioning of Miscanthus Giganteus. *Biomass and Bioenergy*, vol. 109, pp: 166-171, United Kingdom.
[9] Hou, J., Bai, J., Yao, E., Zhu, H., (2020), Design and Parameter Optimization of Disc Type Cutting Device for Castor Stem. *IEEE Access*, vol. 8, pp: 191152-191162, United States.
[10] Jiang, Y., Zhang, J., Nan, Z., Wang, L., (2016), Competitiveness analysis of alfalfa international trade in China (中国苜蓿国际贸易竞争力分析). *Pratacultural Science*, vol. 33, no. 2, pp: 322-329, Gansu/China.
[11] Johnson, P.C., Clementson, C.L., Mathanker, S.K., Grift, T.,Hansen, A.,(2012), Cutting energy characteristics of Miscanthus x giganteus stems with varying oblique angle and cutting speed. *Biosystems Engineering*, vol. 112, no. 1, pp: 42-48, United States.
[12] Li, X., Yin, X., Zhou, X., Li, P., (2020), Countermeasures and Suggestions for High Quality Development of Forage Industry in China (我国饲草产业高质量发展的对策和建议). *ACTA AGRESTIA SINICA*, vol. 28, no. 4, pp: 889-894, Beijing/China.
[13] Li, Z., (2014), Design and Experiments of the Rape Disc-cutter (圆盘式油菜切割器的设计与试验). MSc Thesis, Hunan Agricultural University, Hunan/China.
[14] Otroshko S.A., Shevtsov A.V., Sharikov N.D., (2021), An innovative technical solution to the issue of conditioning forage grasses. *IOP conference series Earth and environmental science*, vol. 901, no. 1, ISSN: 1755-1307, pp: 012049, United Kingdom. DOI: 10.1088/1755-1315/901/1/012049
[15] Song, Y., Wang, Z., Wu, K., Li, F., Song, Z., Yang, X., (2020), Fabrication of Self-sharpening Blades with Metalloceramics Materials and Low-damaged Cutting Mechanism of Alfalfa (金属陶瓷自磨刃割刀对苜蓿低损伤切割机理分析). *Transactions of the Chinese Society for Agricultural Machinery,* vol. 51, no. 10, pp: 421-426, 309 Beijing/China.
[16] Shi, Y., Chen, M., Wang, X., Zhang, Y., Odhiambo, M., (2017), Dynamic Simulation and Experiments on Artemisia selengensis Orderly Harvester Cutter (芦蒿有序收获机切割器动力学仿真与试验). *Transactions of the Chinese Society for Agricultural Machinery,* vol. 48, no. 2, pp: 110-116, Beijing/China.
[17] Vasiliev N., Kudryavtsev A., Golubev A., Vyacheslav, V., (2021), Research Results of the Modified Working Tool of the Combined Rotary Mower. *Agricultural Engineering* (Moscow), no. 3, pp: 10-18, Moscow/Russia.
[18] Wu, B., (2017), *Optimization and Experimental Study on Mechanical System of Alfalfa Mower Conditioner (苜蓿刈割压扁收获机械系统的优化和试验研究)*. PhD Thesis, China Agricultural University, Beijing/China.
[19] Wang, D., He, C., Wu, H., You, Y., (2017), Review of Alfalfa Full-mechanized Production Technology (苜蓿生产全程机械化技术研究现状与发展分析). *Transactions of the Chinese Society for Agricultural Machinery,* vol. 48, no. 8, pp: 1-25, Beijing/China.
[20] Xie, S., Zhao, H., Yang, S., Xie, Q. Yang, M., (2020), Design, Analysis and Test of Small Rotary Lawn Mower of Single-Disc Type. *INMATEH Agricultural Engineering,* vol. 62, no. 3, pp: 89-98, Cuernavaca/Mexico.
[21] Zhao, M., Zhang, N., Yang, T., Shi, Y., (2014), Design and Experiment of Virtual Prototype of Double Disc Mower Cutter (双圆盘割草机切割器虚拟样机设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, vol. 45, no. 8, pp: 101-105, Beijing/China.
[22] Zhu, H., Jin, J., (2022), An Empirical Analysis on the Development of Alfalfa Forage Industry from the Perspective of Grain Security. *Animal Husbandry and Feed Science*, vol. 43, no. 4, pp: 73-79, United States.
[23] Zhang, C., Chen, L., Xia, J., Zhang, J., (2019) Effects of blade sliding cutting angle and stem level on cutting energy of rice stems. *International Journal of Agricultural and Biological Engineering,* vol. 6, no. 12, pp: 75-81, United States.