KINEMATIC ANALYSIS AND EXPERIMENT OF CORN STRAW SPREADING PROCESS /
秸秆抛撒过程动力学分析与试验

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DOI: https://doi.org/10.35633/INMATEH-58-09

Keywords: *straw, kinematic analysis, spreading process, parameter optimization*

ABSTRACT
Aiming at solving the problem of corn straw uneven-distribution of straw retention machine in North China, based on kinematic analysis, the straw spreading process and its straw dynamics model was studied. Then, effects of spreading angle (SA), spreading deflection angle (SDA) and height of guide vane (HGV) on straw spreading distance, width and uniformity were analyzed. Taking SA, SDA and HGV as experimental factors, the straw spreading distance, width and uniformity were used as experimental indicators. Then the optimization experiment of Box-Behnken design corresponding surface was conducted to obtained batter operating parameter of experimental factors. Simultaneously, mathematical regression model of experimental factors and indicators was established. The test results shown that SA, SDA and HGV had extremely significant effects on width, distance and uniformity of straw spreading, respectively; The SA had extremely significant effect on straw spreading uniformity, the SDA and HGV had significant effect on straw spreading uniformity; The interaction between SA and SDA had extremely significant effect on straw spreading distance and significant effect on spreading uniformity. Furthermore, through parameter optimization test, the better combination of parameters of SA, SDA and HGV were 20°, 11.51°, and 1.12m, respectively. By field test under working condition of better parameters combination, the test results shown that width, distance and uniformity of straw spreading was 2.58m, 3.89m and 95.8%, respectively. The error between the test and theoretical prediction value was less than 5%, proved the accuracy of the model. The study can provide theoretical reference for parameters design of straw choppers.

摘要
针对北方一年两熟区，现有秸秆还田机秸秆抛撒不均，影响后续播种作业等问题，本文基于动力学分析，研究秸秆的抛撒运动过程，建立相对应过程的秸秆运动学模型，分析各因素对于秸秆抛撒距离、幅宽和均匀性的影响规律。以秸秆抛射角、抛射偏角和导向叶片离地高度为试验因素进行 Box-Behnken design 响应面优化试验，结果表明，抛射角、抛射偏角和导向叶片离地高度均对秸秆抛撒幅宽和距离有极其显著影响，抛射角与抛射偏角之间交互作用对秸秆抛撒距离有极其显著影响；抛射角对秸秆抛撒均匀具有极其显著的影响，抛射偏角、导向叶片离地高度、抛射角与抛射偏角之间交互作用对秸秆抛撒均匀性有显著影响；通过参数优化，得到较优参数组合为秸秆抛射角为20°，秸秆抛射偏角为11.51°，导向叶片离地高度为1.12m。进行田间试验验证，在较优参数组合作业条件下，抛撒幅宽为2.58m，抛撒距离为3.89m，抛撒均匀度为95.8%，试验结果与理论预测值的误差均低于5%，证明了模型的准确性，满足秸秆抛撒技术要求。本文的研究结果为秸秆粉碎还田机参数的设计提供理论参考。

INTRODUCTION

Straw retention is an important technology to improve soil fertility *(Zhao et al.,2014, Zhang et al., 2016)*, which enhances the content of soil organic carbon and water, reduces the soil bulk density, and then increases crop yield *(Zhao et al., 2015, Yeboah et al., 2017, Akhtar et al., 2018)*. Straw chopping and spreading machine is the main device to realize the straw mechanized retention. The straw spreading capability of the machine directly impacts the effectiveness of straw retention operation.

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However, the straw retention machine has problems such as uneven straw spreading quality and straw pile, which seriously affects the subsequent no-tillage sowing operation and crop growth *(Botta et al., 2015)*.

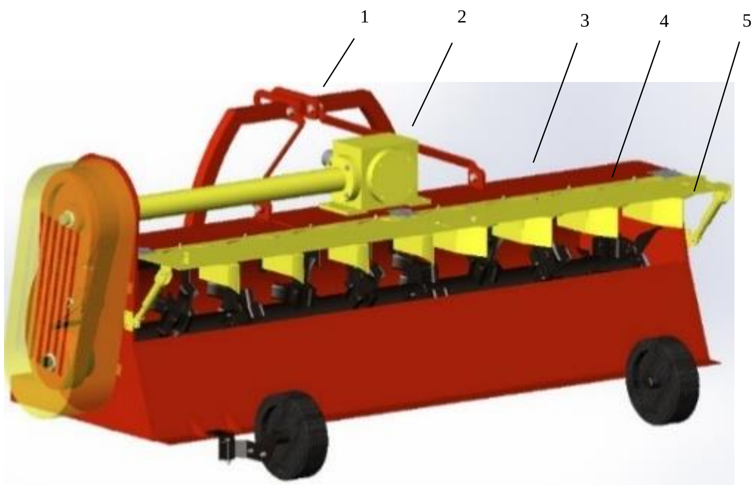
The instalment of straw spreading device in agricultural machine is the main technical means to achieve the straw uniform distribution after chopping and unaffected the follow-up operation. There are some researches on rice and wheat straw spreading in rice and wheat combine harvesters. For example, *Liu et al (2016)* designed the 4DMQ-35A wheat and rice straw chopping and spreading device, which was used in rice and wheat combine harvests to real-time regulate straw spreading uniformity. *Wang et al (2018)* designed a bran dual-scattering wheel mechanism and an adjustable horizontal double-regulating mechanism to improve the straw spreading uniformity. *William et al (2008)* installed high-pressure fans behind the rice-wheat combine harvester to increase the straw spreading initial velocity, thereby increasing the uniformity of crop straw on the soil surface. In the corn stalk retention to field, more researches focused on the straw chopping quality, less research on corn stalk spreading. In the kinematic analysis of agricultural material spreading, there are many kinematic analysis of granular fertilizer. *Dong et al (2013)* established kinematic equation of fertilizer granules to analyse working performance of the cone disc type spreading mechanism. *Zhang et al (2012)* established the fertilizer granules kinematic equation by analyzing the stress state of the granular fertilizer staying and leaving the spreading disc. *Lv et al (2016)* through kinematic analysis of the fertilizer granules in the spreading disc, blades and air, build a kinematic model. However, there are few studies focus on corn straw kinematic analysis. In the early stage, our research team designed a corn straw chopping and spreading machine with spreading guide device to improve the straw spreading uniformity *(Zhang et al., 2017)*.

Therefore, based on kinematic analysis, this study analyzed the straw spreading motion characteristics in operation of the corn straw chopping and spreading machine, built the straw kinematic equation, researched the effect of various factors on straw spreading performance, and finally obtained structural parameters with better spreading performance. This study provides theoretical and technical support for the optimization and improvement of straw chopping and spreading machine.

MATERIALS AND METHODS

Test Materials

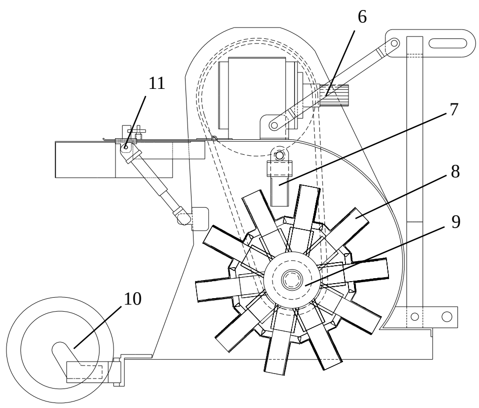
The self-developed straw chopping and spreading machine (fig.1 and fig.2) was selected to analysis the straw spreading mechanism and test the spreading performance. The straw chopping and spreading machine was mainly composed of shell, chopping device (included chopping knife shaft, chopping knife and stationary knife), spreading device (included guide vane, deflector and guide vane regulating device) and transmission. In the operation of the machine, the straw spreading width, distance and uniformity was changed by regulating deflector and guide vanes.



Three-dimensional diagram

Fig. 1 - Structure of straw chopping and spreading machine

1.Suspension device; 2. Transmission; 3. Shell; 4. Deflector; 5. Guide vane; 6. Power input shaft; 7. Stationary knife; 8. Chopping blade; 9. Chopping blade shaft; 10. Walking device; 11. Guide vane regulating device

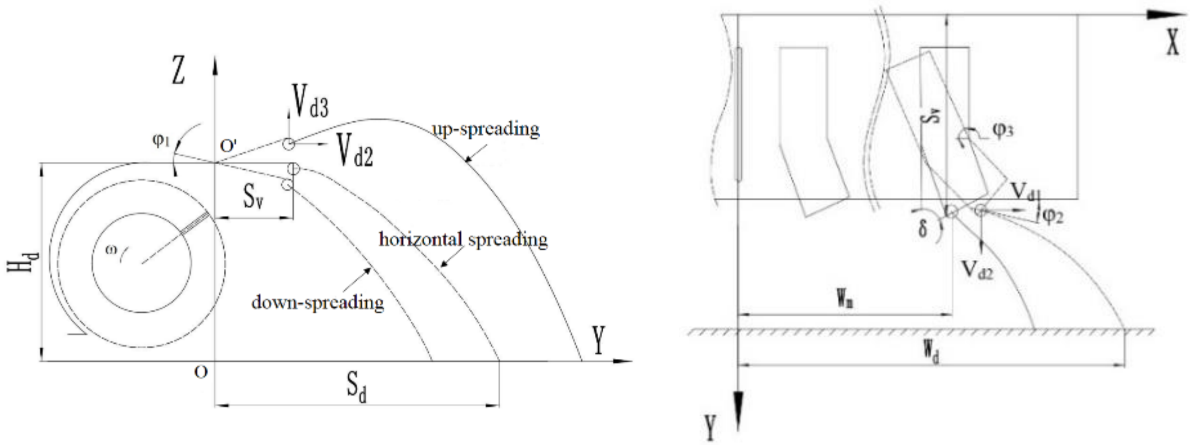


Side view

Fig. 2 - Structure of straw chopping and spreading machine

1.Suspension device; 2. Transmission; 3. Shell; 4. Deflector; 5. Guide vane; 6. Power input shaft; 7. Stationary knife; 8. Chopping blade; 9. Chopping blade shaft; 10. Walking device; 11. Guide vane regulating device

Analysis of corn spreading process



a) Trajectory of straw spreading on YOZ plane *b) Trajectory of straw spreading on XOY plane*

Fig. 3 - Two-dimensional surface trajectory of straw spreading process

In operation, after the straw had been chopped to pieces, the straw spreading process was divided into three parts: straw up-spreading process ($\varphi_1>0$), straw horizontal spreading process ($\varphi_1=0$) and straw down-spreading process ($\varphi_1<0$). The initial velocity of straw in the X, Y, and Z directions was changed by regulating the rotation angle of guide vane and deflector. Therefore, the straw spreading distance, width and uniformity were transformed. In the previous study, the length range of straw chopped to pieces was about 0-10 cm, the maximum airflow speed was about 13.5 m/s in the outlet of machine shell (O' point, initial point of chopped straw leaving the machine shell) (*Zhang et al., 2017*). So, the effect of straw rotation, interaction between straw, straw shape and angle between straw on straw spreading distance and width was small.

For simplifying the straw spreading model, the chopped straw was used as material point.

The straw initial velocity in the O' point was calculated as:

$$V_{d1}=\frac{\cot\varphi_2}{\sqrt{1+\tan^2\varphi_1+\cot^2\varphi_2}}V_d \tag{1}$$

$$V_{d2}=\frac{1}{\sqrt{1+\tan^2\varphi_1+\cot^2\varphi_2}}V_d \tag{2}$$

$$V_{d3}=\frac{\tan\varphi_1}{\sqrt{1+\tan^2\varphi_1+\cot^2\varphi_2}}V_d \tag{3}$$

and $\varphi_2=\varphi_3+\delta-\frac{\pi}{2}$.

where:

V_d was straw spreading initial velocity, m/s;

V_{d1}, V_{d2} and V_{d2} were the initial velocity of straw in the X, Y, and Z directions, respectively, m/s;

φ_1 (spreading angle) was the angle between deflector and horizontal plane, °;

φ_2 (spreading deflection angle) was the angle between spreading initial velocity (V_d) and X-axis, °;

φ_3 was the angle at which the guide vanes rotate around the X-axis,°;

δ, a constant, was related to the structure of the guide vanes.

The air resistance was proportional to the square of the velocity in the study (*Zhang and Chen, 2009*). The straw kinematic equation in spreading process was calculated as:

$$\frac{d^2x}{dt^2} + k_{ar}(\frac{dx}{dt})^2 = 0 \tag{4}$$

$$\frac{d^2y}{dt^2} + k_{ar}(\frac{dy}{dt})^2 = 0 \tag{5}$$

$$\frac{d^2z}{dt^2} + (-1)^n k_{ar}(\frac{dz}{dt})^2 + g = 0 \tag{6}$$

where:

x was the horizontal spreading distance of straw, m;

y was straw backward spreading distance, m;

z was the vertical spreading distance of straw, m;

t was the time of chopped straw from leaving the apparatus to falling on the ground, s;

k_{ar} was air resistance factor, m^{-1};

n was the direction coefficient of air resistance,

g was the gravitational acceleration, m/s^2.

So, in the straw up-spreading process, the direction of air resistance was consistent with the direction of gravity, n=2, while in the straw down-spreading process and horizontal spreading process, the direction of air resistance was opposite to the direction of gravity, n=1.

The k_{ar} was affected by the straw characteristics, such as shape, size and quality (*Liu and Qian, 2017*), calculated Eq. (7).

$$k_{ar} = \frac{\rho_{air} C_{air} A_{air}}{2m_3} \tag{7}$$

where:

m_3 was the mass of the chopping straw, kg;

ρ_{air} was the air density, kg/m^3;

C_{air} was the air damping coefficient;

A_{air} was the resistance area, m^2.

Meanwhile, by referring to the study of *Gorial et al (1990)*, m_3=3.212×10^{-4} kg, A_{air}=1.823×10^{-4} m^2, C_{air}=0.81, ρ_{air}=1.29 kg/m^3, so k_{ar}=0.297m^{-1}.

According to equation (4) - (6), the straw position coordinate of the XOY plane in the spreading process and motion time in the air can be obtained, thereby obtaining the straw spreading width S_w and spreading distance S_d.

$$x(t) = S_w = W_m + \frac{1}{k_{ar}}\ln(1 + k_{ar}V_{d1}t) \tag{8}$$

$$y(t) = S_d = S_v + \frac{1}{k_{ar}}\ln(1 + k_{ar}V_{d2}t) \tag{9}$$

$$t=\begin{cases}\sqrt{\dfrac{1}{gk_{ar}}}\ln\left[\dfrac{e^{\arctan(\sqrt{\frac{k_{ar}}{g}}V_{d3})}}{e^{k_{ar}H_d}\sqrt{\dfrac{k_{ar}}{g}V_{d3}^2+1}-\sqrt{(\dfrac{k_{ar}}{g}V_{d3}^2+1)e^{2k_{ar}H_d}-1}}\right] & \varphi_1>0 \quad (10)\\ \sqrt{\dfrac{1}{gk_{ar}}}\ln(e^{k_{ar}H_d}+\sqrt{e^{2k_{ar}H_d}-1}) & \varphi_1=0 \quad (11)\\ \sqrt{\dfrac{1}{gk_{ar}}}\ln\left[\dfrac{e^{k_{ar}H_d}+\sqrt{e^{2k_{ar}H_d}+\dfrac{k_{ar}}{g}V_{d3}^2-1}}{1+\sqrt{\dfrac{k_{ar}}{g}}V_{d3}}\right] & \varphi_1<0 \quad (12)\end{cases}$$

where:

H_d was height of guide vane, m;

W_m was distance between guide vane and deflector centre line, m;

S_v was front distance of guide vane, m.

The equation (10), (11) and (12) were represented the straw motion time of up-spreading, horizontal-spreading and down-spreading process, respectively.

Therefore, in the straw spreading process, it can be confirmed that the straw spreading width and distance were affected by distance between guide vane and deflector centre line (W_m), height of guide vane (H_d) and front distance of guide vane (S_v).

Test site

According to analysis of spreading process, the straw spreading test was carried out in the Agricultural Science and Technology Park of China Agricultural University, Hebei Province (115°56'E, 39°28'N) to obtain the optimal working parameters of the straw spreading device (W_m, H_d, S_v).

The test site is wheat-corn cropping system, the row spacing, the plant spacing, average diameter, average height and average moisture of corn were 620 mm, 234 mm, 19 mm, 2290 mm and 78.4%, respectively. In the test process, the rotate speed of the chopping knife shaft was 2100 rpm *(Zhang et al., 2017).*

Test plane

According to the theoretical analysis of straw spreading process and previous complete randomized design, the SA (φ_1), SDA (φ_2) and HGV (H_d) were the main influence factors of straw spreading performance. The working parameters (φ_1, φ_2, H_d) were changed by adjusting the guide vane regulating device position and direction to obtain the different spreading width, distance and uniformity. Each group of straw test area was measured along the width and distance of the machine to measure the spreading width and distance, and the average width and distance of the straw was calculated. Six square test points with an area of 0.2 m × 0.2 m were selected to test the weight of straw.

The percentage of straw weight in each area to the total straw weight of test site was calculated by Christiansen Uniformity Coefficient to obtain the straw spreading uniformity (*Sun and Feng, 2016, Kumhála et al., 2005*), computed as:

$$C_u=[1-(\sum_{i=1}^{6}\left|W_{si}-W_m\right|/6W_m)] \tag{13}$$

Where:

W_{si} was straw weight in *i*-th region, kg;

W_m was arithmetic mean of the weight of straw in 6 regions, kg.

Fig. 4 - Straw spreading field test

Orthogonal experimental design

According to pre-single factor experiment, the SA (φ_1), SDA (φ_2) and HGV (H_d) were selected as influence factors, the spreading width, distance and uniformity were the response values. The test factor and code levels were shown in Table.1. The design principle of Box-Behnken was used to design the test as Table 2 and per test was repeated 3 times. The test output was shown in Table 2.

Table 1

Factors and code levels of tests

	Coded value	Factor		
		SA/°	SDA /°	HGV /m
Down level	-1	-15	4	1.07
Zero level	0	2.5	47	1.10
Upper level	1	20	90	1.12

Table 2

Box-Behnken's design and corresponding result

Test groups	Influence Factors			Response Values		
	SA/° *A*	SDA /° *B*	HGV/m *C*	Width/m P_1	Distance/ m P_2	Uniformity/% P_3
1	-15	47	1.12	2.22	2.95	83.12
2	20	47	1.07	2.17	3.53	90.03
3	2.5	90	1.12	2.11	3.43	84.03
4	20	90	1.095	2.21	3.72	90.37
5	20	4	1.095	2.52	3.2	97.39
6	2.5	47	1.095	2.28	3.18	83.43
7	2.5	4	1.07	2.39	3.08	84.36
8	2.5	47	1.095	2.3	3.22	82.63
9	-15	4	1.095	2.39	2.73	87.17
10	-15	47	1.07	2.18	2.85	80.46
11	2.5	47	1.095	2.29	3.2	81.53
12	2.5	4	1.12	2.42	3.13	88.23
13	-15	90	1.095	2	2.9	88.18
14	20	47	1.12	2.46	3.62	90.23
15	2.5	47	1.095	2.24	3.19	80.43
16	2.5	47	1.095	2.33	3.21	79.63
17	2.5	90	1.07	1.98	3.34	79.34

RESULTS

Establishment of regression equations and significance analysis

The Design-Expert 8.0.6 software was used to perform multiple regression fitting and analysis of variance on straw spreading test data (Table.2). A quadratic polynomial regression mathematical model was built for revealing the effects of the three factors on the straw spreading width (P_1), spreading distance (P_2), and spreading uniformity (P_3). The optimized mathematical regression model was equation (12) after deleting the not-significant factors.

$$\begin{cases} P_1=2.28+0.071A-0.18B+0.061C+0.063AC-0.043C^2 \\ P_2=3.2+0.33A+0.16B+0.041C+ \\ \quad 0.087AB-0.035A^2-0.027B^2+0.072C^2 \\ P_3=80.7+3.67A-1.9B+1.47C-2.01AB+5.72A^2+3.82C^2 \end{cases} \tag{14}$$

where:

P_1 was straw spreading width, m;
P_2 was straw spreading distance, m;
P_3 was straw spreading uniformity, %;
A was SA (-15°≤A≤-20°);
B was SDA (4°≤B≤90°);
C was HGV (1.07m≤C≤1.12m).

The regression model variance was shown in Table 3. For the whole quadratic regression analysis, the effect order of the factors to the straw spreading width were SDA (P<0.0001)> SA (P=0.0009) > HGV (P=0.0022) which were extremely significant (P<0.01). The *F* value of SA and HGV were similar, indicating that the two factors had similar effects on the straw spreading width and were smaller than the SDA. The interaction between SA and HGV was significant (P=0.0114). The squared term of HGV had a significant influence on the straw spreading width (P=0.0484). The effect of the factors to the straw spreading distance were SA (P<0.0001, F=1573.78) > SDA (P<0.0001, F=352.82) > HGV (P=0.0016). The interaction between SA and SDA was extremely significant(P=0.0001), the squared term of SA (P=0.0185), SDA (P=0.0467) and HGV (P=0.004) had a significant influence on the straw spreading distance. The effect of the factors to straw spreading uniformity were SA (P=0.0003)> SDA (P=0.011) > HGV (P=0.037). The *F* value of SDA and HGV was similar, indicating that the two factors had similar effects on the straw spreading uniformity and were smaller than SA. The interaction between SA and SDA (P=0.0378) was significant, the squared term of SA (P=0.0002) was extremely significant influence on the straw spreading uniformity and the squared term of SDA (P=0.0021) was significant influence on the straw spreading uniformity

Table 3

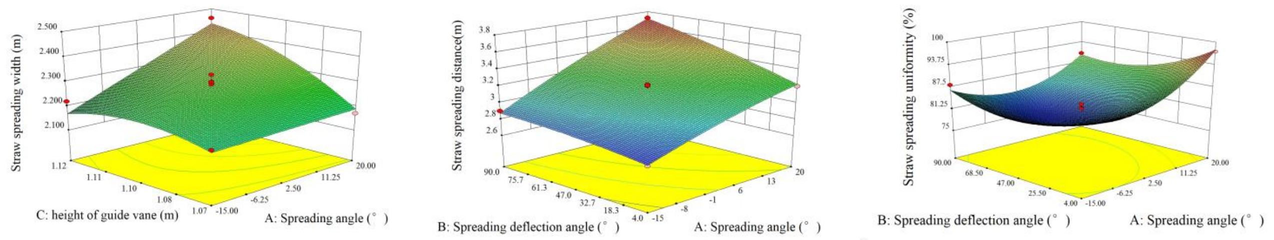
Variance analysis of regression model

Test index	Width P_1		Distance P_2		Uniformity P_3	
	***F* Value**	***P* Value**	***F* Value**	***P* Value**	***F* Value**	***P* Value**
Model	29.00	<0.0001	228.85	<0.0001	16.6	0.0006
A	30.07	0.0009	1573.78	<0.0001	42.88	0.0003
B	186.6	<0.0001	352.82	<0.0001	11.75	0.011
C	22.22	0.0022	24.59	0.0016	6.61	0.037
AB	1.18	0.3125	55.32	0.0001	6.53	0.0378
AC	11.57	0.0114	0.045	0.8378	0.61	0.4592
BC	1.85	0.2159	0.72	0.4234	0.068	0.80.16
A^2	0.47	0.516	9.32	0.0185	53.69	0.0002
B^2	1.28	0.2955	5.75	0.0476	22.6	0.0021
C^2	5.7	0.0484	39.98	0.004	2.37	0.1675
Lack of fit	1.61	0.3201	3.83	0.1135	1.06	0.4605

Note: P<0.1was significant; P<0.05 was quite significant; P<0.01 was extremely significant.

Response surface interaction analysis

In order to visually analyse the relationship between the test indicators and various factors, the Design-Expert 8.0.6 software was used to obtain the response surface of significant interaction factors (Fig.5).



a) P_1（A,47,C） b) P_2（A,B,1.1） c) P_3（A,B,1.1）

Note: the test factors and level of response surface was shown in Table 1, the response value was shown in Table 2.

Fig. 5 - Effects of test factors on test index

In the case of the SDA of 47°, the response surface of the significant interaction term on the test factors was shown in Figure 5.a.

When SA was in the range of -15° to -8°in the response surface, the straw spreading width was increased first and then decreased with the increased of the HGV and the increasing slope was smaller than the decreasing slope. When the range of SA was 6° to 20°in the response surface, the straw spreading width was increased with the increase of guide vane. When the range of HGV was 1.07 m to 1.08 m in the response surface, the effect of SA on straw spreading width was small. When the HGV was larger than 1.10 m in the response surface, the straw spreading width was improved with the increase of SA.

In the case that the HGV was 1.1 m, the SA was 20°, the straw spreading width was the largest with 2.46 m. Combined with the test situation, when the HGV was larger, the motion time of straw in the air was larger, thereby increasing the straw spreading width. With the increased of SA, the collision between deflection and straw was reduced, thereby indirectly increasing the straw spreading width.

When the HGV was 1.1m, the response surface of the significant interaction term on the test factors was shown in Figure 4.b. With the increase of SA and SDA, the straw spreading distance was increased and the effect of the SA on the spreading distance was greater than the effect of the SDA. As the SA increases, the increase rate of spreading distance when the SDA was in the range of 80 °to 90° at higher level was higher than when the SDA was in the range of 4° to 30°. Observing the overall trend of the response surface, the whole image was steeper along the direction of the SA, and the direction along the SDA was placid.

Combined with the test situation, with the increase of SA and SDA, the straw velocity on the direction of spreading distance was increased and finally the straw spreading distance was increased. Combined with the test situation, with the increase of the SA and the projectile declination, the speed of the straw along the spreading distance increased, which resulted in the increasing of straw spreading distance. When the SA was 20°, the SDA was 90°, the straw spreading distance was largest with 3.72 m. Therefore, in order to obtain a higher spreading distance in actual operation, the SA and SDA should be kept at higher level.

Setting the height of guide vane as 1.1m, the response surface of the significant interaction term on the test factors was shown in Figure 4.c. In the response surface, with the increase or decrease of SA, the spreading uniformity was increased first and then decreased, and the increased rate of spreading uniformity was higher than the decreased rate. When the SA was in the range of 2.5° to 20°, the spreading uniformity was increased with the increase of SDA; when the SA was in the range of -15° to 2.5°, the straw spreading uniformity was fist increased and then decreased with the increase of SA and the increased rate was higher than the decreased rate. In the test process, when the SA was larger and the SDA was smaller, the angle between the two guide vanes in the middle of the spreading device was greater than 90°, thus, in the straw spreading process, most of straw was guided with larger velocity on the direction of spreading width to increase the straw spreading range, thereby increasing the straw spreading uniformity.

Parameter optimization

When the spreading width and distance reached the maximum value, the range of straw spreading could be maximized, which resulted in the improving of the straw spreading uniformity. In order to obtain the optimal parameters of straw spreading device, the optimization model of Design-Expert 8.0.6 software was used to solve the constrained target optimization of the regression model above.

The equation (13) was as follow.

$$maxP=\begin{cases} maxP_1(A,B,C) \\ maxP_2(A,B,C) \\ maxP_3(A,B,C) \end{cases} \quad (13)$$

and $-15 \le A \le 20, 4 \le B \le 90, 1.07 \le C \le 1.12$.

Where:

P_1 was straw spreading width, m;

P_2 was straw spreading distance, m;

P_3 was straw spreading uniformity, %;

A was SA; *B* was SDA; *C* was HGV.

The combination of the highest satisfaction parameter values by software were A=20°, B=11.51°, C=1.12m, and the predicted values of the three evaluation indexes under this parameter combination were P1=2.58m, P2=3.89m and P3 = 97.39%.

Test verification

In order to verify the optimal combination of straw chopping and spreading machine, the SA, SDA and HGV were adjusted to 20°, 11.51° and 1.12 m respectively and the test was repeated three times.

The results were shown in Table 4.

Table 4

Test results verification

Number	Distance (m)	Width (m)	Uniformity (%)
1	2.57	3.68	94.5
2	2.62	3.85	96.2
3	2.46	3.4	96.7
Mean	2.55	3.79	95.8
Theoretical Value	2.58	3.89	97.39

The field test results shown that under the optimal combination of parameters, the straw spreading distance was P_1=2.55m, spreading width was P_2=3.79m and spreading uniformity was P_3=95.8%. The error between the test value and the theoretical prediction value was less than 5%, so the above prediction model was reliable.

CONCLUSIONS

The straw spreading process determined the straw spreading quality of the straw chopping and spreading machine. In this paper, the straw spreading process was deeply studied and the kinematic equation of straw movement was obtained and verified by test. The specific conclusions were as follows:

1. The straw spreading process of straw chopping and spreading machine was divided to straw up-spreading process, straw horizontal spreading process and straw down-spreading process. The kinematic model of straw spreading process was built and the spreading angle, spreading deflection angle, height of guide vane were the key parameters to effect straw spreading width, distance and uniformity.

2. Using the field test, the effect of SA, SDA and HGV on the straw spreading distance, width and uniformity was determined by the Box-Behnken design response surface optimization method. The regression mathematical model was used to optimize the analysis to obtain the optimal combination of spreading parameters: SA was 20°, SDA was 11.51° and HGV was 1.12m. By field straw spreading test, the result shown that spreading width, distance and uniformity was 2.58m, 3.89m and 95.8%, respectively. The error between the test result and the theoretical prediction value was less than 5%.

ACKNOWLEDGMENT

The authors thank Dr.Wei Zhongcai, Dr.Zhao Hongbo, Dr.Liu Wenzheng, Dr.Lou Shangyi and Dr.Cheng Xiupei for technological help. Financial support for this research was provided by Modern Agricultural Industry Technology System (Grant No. CARS-03), the Program for Changjiang Scholars and Innovative Research Team in University of China (Grant No. IRT13039) and Special Fund for Agro-scientific Research in the Public Interest from the Ministry of Agriculture, China (Grant No. 201503136).

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