ESTABLISHMENT AND CALIBRATION OF DISCRETE ELEMENT MODEL OF KING GRASS STALK BASED ON THROWING TEST
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基于抛送试验的王草茎秆离散元模型参数标定

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ABSTRACT
In order to better use the discrete element method (DEM) to study the cutting and throwing process of King Grass (KG) stalk in mechanical harvesting, the DEM model and contact parameters of KG stalk were studied in this paper. By using the Multi-sphere method, the DEM model of KG stalk was established in EDEM software. Through the impact bounce test and slope sliding test, the stalk-steel coefficient of static friction, stalk-steel coefficient of restitution and stalk-stalk coefficient of restitution were calibrated as 0.372, 0.656 and 0.523, respectively. Based on the stacking test, using the response surface methodology, the optimal values of stalk-stalk coefficient of static friction, stalk-stalk coefficient of rolling friction, stalk-steel coefficient of rolling friction were calibrated as 0.393, 0.072 and 0.144, respectively. The throwing test bench of stalk was designed, and the actual and simulation throwing test were carried out. The relative error of throwing distance in bench test and simulation test under four throwing speeds was 1.15%, 7.76%, 8.88% and 10.46%, respectively. The throwing trajectory curve of the simulation test is consistent with that of the actual test, which verifies the accuracy of the DEM model and contact parameters of KG stalk.

摘要
为更好的应用离散元法研究王草茎秆与收获机械的作用机理，寻求王草茎秆离散元模型的最优接触参数组合。论文对王草茎秆的物理参数进行测量，并基于多球粘结颗粒模型在 EDEM 软件中建立了王草茎秆的离散元模型；采用台架试验和仿真试验相结合的方式，通过碰撞弹跳试验和斜面滑动试验，得到茎秆-钢板静摩擦因数、王草茎秆-钢板碰撞恢复系数和茎秆-茎秆碰撞恢复系数依次为 0.372、0.656 和 0.523；基于堆积试验，利用响应面优化方法，以 EDEM 仿真堆积角与实际堆积角的相对误差为指标，确定茎秆-茎秆静摩擦因数、茎秆-茎秆滚动摩擦因数以及茎秆-钢板滚动摩擦因数的最优数值分别为 0.393、0.072 和 0.144；进行王草茎秆实际抛送试验和CFD-DEM 气固耦合仿真抛送试验，得到不同抛送板转速（400、500、600 和700 $r\cdot min^{-1}$）条件下，台架试验和仿真试验抛送距离的相对误差分别为 1.15%、7.76%、8.88%和 10.46%，仿真试验的茎秆抛送轨迹曲线与台架试验抛送轨迹曲线相吻合，验证了王草茎秆离散元模型和接触参数的准确性。

INTRODUCTION
King Grass (Pennisetum Americanum × P. purpureum, KG) is mainly planted in south of China and other tropical and subtropical regions globally (*Zhao et al., 2019*). KG is a high-yield biological resources and it is extensively used in ecological environmental protection, bioenergy industry, and animal husbandry (*Li et al., 2019*). In order to improve the harvest level and economic benefit, it is necessary to develop suitable mechanical equipment for KG harvest. In recent years, simulation software EDEM based on discrete element method (DEM) has been widely used in agricultural equipment research. The chopped KG stalk can be regarded as granular. The application of DEM to study the mechanism of KG stalk and harvester in the process of cutting and throwing can provide a theoretical basis for machine design and optimization. In the DEM simulation, it is necessary to establish a DEM model and define the contact parameters of the model, including coefficient of static friction (CSF), coefficient of rolling friction (CRF) and coefficient of restitution (CR). Many scholars had carried out extensive research on the DEM model and contact parameters of soil (*Tran et al.,*

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2020), fertilizer (*Bangura et al., 2020*), seed (*Guzman et al., 2021; Ma et al., 2020*) and other materials. In recent years, the research on the DEM model of stalk has also been reported. *Liao et al. (2020)* took forage rape as the research object, determined the main parameters of DEM model through stalk bending failure simulation test and response surface analysis, such as normal contact stiffness, tangential contact stiffness, critical normal stress and critical tangential stress. Based on the results of Alfalfa straw physical test, *Ma et al. (2020)* determined the parameters of Alfalfa stalk DEM model by using Plackett-Burman test, steepest climbing test and Box-Behnken test. *Zhang et al. (2020)* determined the optimal combination of corn straw parameters by using results of mechanical corn stalk tests, DEM simulations of impact fracture, compression fracture.

Compared with soil, fertilizer, seeds and other materials, the size and mass of KG stalk are different. At the same time, compared with alfalfa, forage rape and other forages, its stalk diameter is larger, and the DEM model is more difficult to calibrate. In this research, the KG stalk after cutting was taken as the research object. The DEM model of KG stalk was established in EDEM software. The contact parameters were calibrated by bench test and simulation test. The stalk throwing test bench was built to carry out the actual throwing test. The CFD-DEM coupling method was used to carry out the simulation throwing test. By comparing the results of actual test and simulation test, the accuracy of DEM model and contact parameters was verified. The objective of this study is to provide model and parameter support for the application of DEM to study the interaction mechanism between KG stalk and harvester, and provide a DEM model verification method for stalk based on throwing test.

MATERIALS AND METHODS

Physical model of KG stalk

In order to make the DEM model of KG stalk more accurate, it is necessary to establish the stalk profile model of KG through measurement. The stalk of KG was collected from the experimental field of Hebei Xinnong Machinery Co., Ltd. (E:114.822º, N:38.157º), the average plant height was 1.8m during the harvesting period. According to the harvesting requirements, 9FDRFX cutter was used to cut KG, and the average cutting length was 24mm. In order to determine the physical model of KG stalk, 200 stalk segments were randomly selected to observe the stalk shape and measure the stalk diameter with vernier calliper. It was found that the stalk of KG was mainly cylindrical, and some of the stalks were broken along the axis to be semi-cylindrical, and the ratio of cylinder to semi-cylinder was about 4:1. The diameter distribution of cylindrical stalk is shown in Fig. 1. According to the diameter distribution, the cylindrical stalk is divided into small diameter (14 mm < d < 17 mm), medium diameter (17 mm < d < 20 mm) and large diameter (20 mm < d < 23 mm). The average diameter of the three is 15.7 mm, 18.3 mm and 21.2 mm, and the approximate ratio of quantity is 2:5:1.

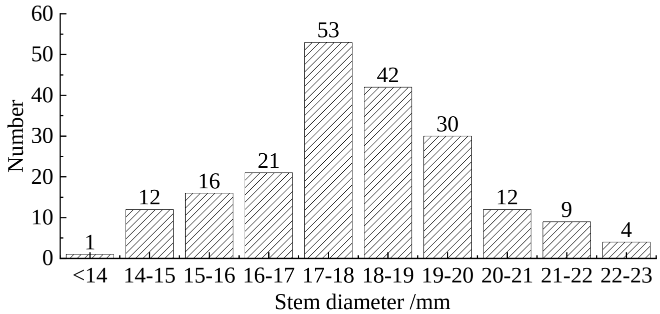


Fig. 1 - Stalk diameter distribution

The DEM model of KG stalk

DEM is a kind of analytical method based on molecular dynamics. During the simulation test, according to the material characteristics of KG stalk, its surface adhesion force is small. Hertz-Mindlin (no-slip) model is adopted for the contact model of KG stalk particles (*Grima et al., 2011*).

The shape of spherical particles is simple, which can be limited by radius and coordinate parameters, and there is only one contact state between spherical particles, which can shorten the simulation time. Therefore, the DEM model of materials is usually established in the form of spherical particle accumulation. When the diameter of spherical particles is smaller, the number of spherical particles required is more, and the shape of DEM model is closer to the actual shape of stalk, but the corresponding computer calculation processing time is longer. Considering comprehensively, using the Multi-sphere method (MSM), the small-diameter stalk, medium diameter stalk and large-diameter stalk were filled with spherical particles with radius of 4 mm, 4.5 mm and 5 mm respectively. The semi cylindrical stalk structure was filled with spherical particles with radius of 2.25 mm and 4.5 mm. Finally, the optimized DEM model of KG stalk was formed, as shown in Fig. 2.

a. Small diameter stalk （15.7mm） b. Medium diameter stalk （18.3mm） c. Large diameter stalk （21.2mm） d. Semi-cylinder stalk （18.3mm）

Fig. 2 - DEM model of KG stalk

Calibration of contact parameters

Due to the difference between the DEM model and the actual shape of stalk, the direct application of the contact parameters measured in the test to the simulation will cause test error. In order to improve the accuracy of the DEM simulation test, this section calibrates the DEM model parameters through the combination of bench test and simulation test.

In the process of harvesting and processing, in addition to the contact and interaction between KG stalks, stalks and mechanical equipment will also have contact. Q235 steel commonly used in agricultural machinery was selected as the contact material in this study. The intrinsic parameters of KG stalk and Q235 are shown in Table 1 (*Rong, 2014; Ma et al., 2020*).

Table 1

Intrinsic parameters

Moisture content of KG	Poisson's ratio of KG	Shear modulus of KG	Density of KG	Poisson's ratio of Q235	Shear modulus of Q235	Density of Q235
[%]	—	[Pa]	[kg/m^3]	—	[Pa]	[kg/m^3]
72±2	0.34	10.45×10^6	1090	0.28	8.2×10^{10}	7850

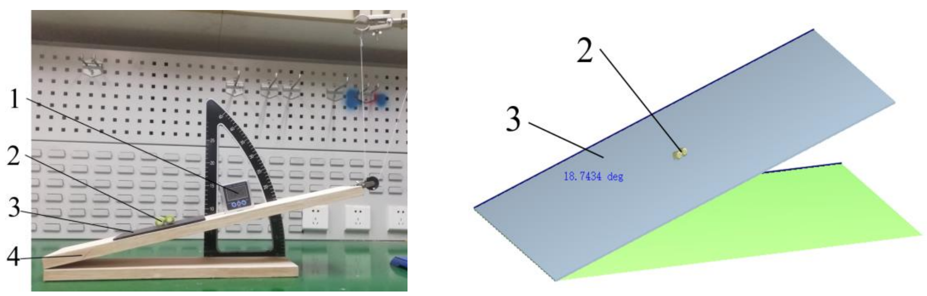
Calibration of Stalk-Steel CSF

CSF is one of the main contact parameters of DEM model, which can be expressed as the ratio of the maximum static friction force (f) to the contact positive pressure (F_N). In this study, the stalk-steel CSF was measured by inclined plane method. The test device is shown in Fig. 3a. The steel plate was fixed on the inclined plate, and the inclined plate was placed horizontally at the beginning. In order to prevent the stalk from rolling and reduce the test error, two sections of stalk were connected in series with pins and placed on the steel plate smoothly. Slowly lift one side of the inclined plate by pulling rope to gradually increase the inclined angle. When they begin to slide, stop lifting, and measure the inclined angle with the angle digital display instrument (Weidu, 4 * 90º, 0.05º, Wenzhou Weidu Electronics Co., Ltd.).

The relation between coefficient of static friction (μ_1) and inclination angle (α) is written as Eq. 1,

$$\mu_1 = f/F_N = tan\alpha \tag{1}$$

In order to improve the accuracy of the test results, considering the influence of the placing state of the stalks, the stalks were placed on the steel plate in transverse, longitudinal and oblique directions. The average value was calculated by seven repeated tests. The results showed that the inclination angles were 22.42°, 22.38° and 22.41° when the stalk was placed horizontally, longitudinally and obliquely. It can be seen that the state of stalk placement had no significant influence on the friction angle. The average friction angle of the three states was 22.40°, and the static friction factor was calculated as 0.41.



(a) Practical test (b) Simulation test

Fig. 3 - Practical test and simulation test of CSF

1 – Angle digital display instrument; 2 – KG stalk; 3 – Steel plate; 4 – Inclined plate;

Setting the physical parameters of stalk particles and plate in the EDEM simulation test (Fig. 3b). CRF, CR and stalk-steel CSF have no effect on the inclination angle of steel plate, so these parameters were set to 0 in order to reduce interference. According to the pre-simulation test, the stalk-steel CSF ranged from 0.25 to 0.55. Seven groups of simulation tests were conducted with step size as 0.05, and each group of tests was repeated for three times to take the average value. The test design scheme and results are shown in Table 2. Using Origin 2018 software to fit the data, the fitting curve is shown in Fig. 6, and the fitting equations for the stalk-steel CSF (x_1) and the steel plate inclination angle (y_1) was established as:

$$y_1 = 7.6856x_1^2 + 46.36x_1 + 4.0672 \tag{2}$$

Table 2

Design scheme and results of simulation test for stalk-steel CR

Stalk-steel CSF x_1	0.25	0.30	0.35	0.40	0.45	0.50	0.55
Inclination angle y_1 **[°]**	1.17	1.05	0.78	0.52	0.47	0.39	0.37

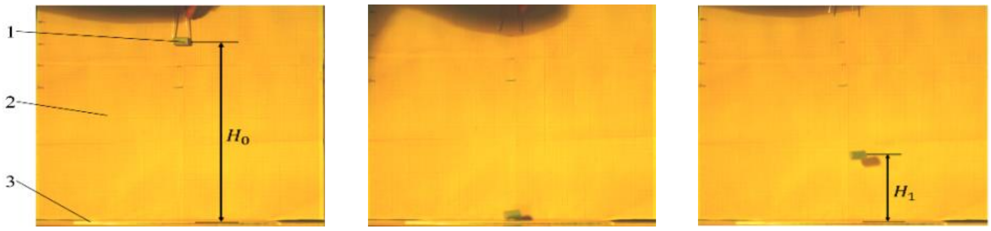
The determination coefficient R^2 of Eq. 2 was 0.9999，indicating that the fitting equation is highly reliable. The steel plate inclination angle of 22.40° measured by bench test was substituted into Eq. 2 to obtain x_1=0.372. The simulation test was carried out with CSF of 0.372, and the value of steel plate inclination angle was measured as 22.373°. The relative error between this result and bench test was 0.12%, which indicates that the calibrated stalk-steel CSF can be used for EDEM simulation, so the stalk-steel CSF was selected as 0.372.

Calibration of stalk-steel CR

The stalk-steel CR was determined by impact bounce test, and the test environment is shown in Fig. 4. KG was released from the initial position, and bounced to the highest point after colliding with the steel plate. The whole process of collision bounce was recorded by high-speed camera (Vision Research, Inc. Phantom v 9.1). The collision process is shown in Fig. 5.

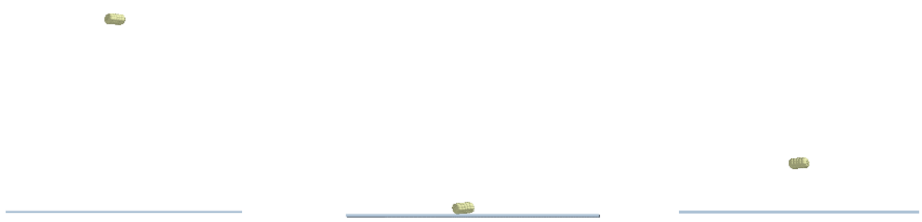
Fig. 4 - Impact recovery test

1 – Fill light; 2 – High-speed camera; 3 – Coordinate paper; 4– Steel plate; 5– Computer



Initial height Impact steel plate Highest jumping point

(a) Bounce test



Initial height Impact steel plate Highest jumping point

(b) Simulation test

Fig. 5 - Test for CR

1– KG stalk; 2– Coordinate paper; 3– Steel plate

The maximum jumping height of the straw was measured by using the image processing software Fiji (ImageJ) with the reference length of coordinate paper dimension. The stalk-steel CR (e_1) can be calculated according to formula 3,

$$e_1 = \frac{v_1}{v_0} = \frac{\sqrt{2gH_1}}{\sqrt{2gH_0}} = \sqrt{\frac{H_1}{H_0}} \tag{3}$$

where:

v_0 is the instantaneous contact velocity, v_1 is the instantaneous separation velocity, H_0 is the initial falling height, H_1 is the maximum jumping height and g is the acceleration of gravity.

It was assumed that in the process of collision, the stalk and steel plate have small deformation at the contact point of collision and the collision time is very short. In order to verify whether the initial release height has influence on the test results, bench impact bounce tests were carried out with initial heights of 300 mm, 350 mm and 400 mm, respectively. The maximum bounce heights of stalk were 83.8 mm, 99.8 mm and 112.7 mm and the stalk-steel CR were calculated as 0.529, 0.534 and 0.531, respectively. The initial release height had no significant effect on the CR. The simulation experiment was carried out with H_0 as 350 mm. The CSF, CRF and stalk-stalk CR have no effect on the rebound height. In order to reduce the interference, the above parameters were set to 0 in EDEM simulation. The results of pre-simulation test showed that the range of stalk-steel CR was 0.40-0.70. Therefore, the step length was set to 0.05, and 7 groups of simulation tests were conducted, and each test was repeated for 3 times. The design scheme and results of the test are shown in Table 3. Using Origin 2018 software to fit the data, the fitting curve is shown in Fig. 7, and the fitting equation of the CR (x_2) and bounce height (y_2) was established as:

$$y_2 = 338.81x_2^{\ 2} - 139.66x_2 + 45.337 \tag{4}$$

Table 3

Design scheme and results of simulation test for coefficient of restitution

Stalk-steel CR x_2	0.40	0.45	0.50	0.55	0.60	0.65	0.70
Bounce height y_2 **[mm]**	44.23	50.36	59.83	70.64	86.15	95.51	114.10

The determination coefficient R^2 of Eq. 4 was 0.9966, which indicates that the fitting equation has high reliability. Substituting H_1=99.8 mm measured in the 350 mm bench test into Eq. 10, it can be obtained that x_2 was 0.656. Then the CR was set to 0.656 in EDEM, and the simulation tests with release heights of 300, 350 and 400mm were carried out. The rebound heights of simulation tests were 80.85 mm, 97.88 mm and 110.41 mm, and the relative errors with the actual experimental rebound heights were 3.65%, 1.96% and 2.07%. It showed that the simulation results after calibration are basically consistent with the bench test, so the stalk-steel coefficient of restitution was selected as 0.656.

Calibration of stalk-stalk coefficient of restitution

Similar to the method of measuring the stalk-steel coefficient of restitution, the steel plate is replaced by the stalk row which was neatly strung together. The KG stalk was clamped with tweezers and releases from the initial position. The stalk fell freely and bounced to the highest point after colliding with the stalk row. The whole process of collision bounce was recorded by high-speed camera. The calculation formula of the stalk-stalk coefficient of restitution is the same as that of formula 3.

The initial release height of stalk was selected as 300 mm, 350 mm and 400 mm respectively. Each group was tested for 10 times and the average value was taken. The average height of stalk bounce was 63.4 mm, 76.7 mm and 85.5 mm respectively. The stalk-stalk CR under the three release heights were 0.459, 0.468 and 0.462, respectively. The initial release height of the stalk had no significant effect on the CR, so the simulation experiment was carried out with H_0=350mm. The CRF and the stalk-stalk CSF have no effect on the bouncing height of stalk. In order to reduce the interference, the above parameters were set to 0 in EDEM simulation. The stalk-steel CSF was set as 0.372, and the stalk-steel CR was set as 0.656. After the pre-simulation test, it was determined that the value range of stalk-stalk CR was 0.30 ~ 0.60. The design scheme of simulation test is shown in Table 4.

Table 4

Design scheme and results of simulation test for CR

Stalk-stalk CR x_3	0.30	0.35	0.40	0.45	0.50	0.55	0.60
Bounce height y_3 **[mm]**	37.69	45.68	55.41	57.17	72.69	82.52	96.75

Fitting the data in Table 4, the fitting curve is shown in Fig. 8, and the fitting equation of the stalk-stalk CR (x_3) and rebound height (y_3) was established as :

$$y_3 = 281.98x_3^2 - 62.241x_3 + 32.073 \tag{5}$$

The determination coefficient R^2 of Eq. 5 was 0.9887, which indicates that the fitting equation has high reliability. By substituting the measured value of 76.7 mm in the 350 mm bench test into Eq. 5, it can be obtained that x_3=0.523. Then the stalk-stalk CR was set as 0.523 in EDEM, and the simulation tests with release heights of 300 mm, 350 mm and 400 mm were carried out. The rebound heights of the simulation tests were 60.36 mm, 73.51 mm and 79.68 mm, and the relative errors with the actual experiments were 4.80%, 4.16% and 6.81%. It showed that the simulation results after calibration were basically consistent with the bench test, so the stalk-stalk coefficient of restitution was selected as 0.523.

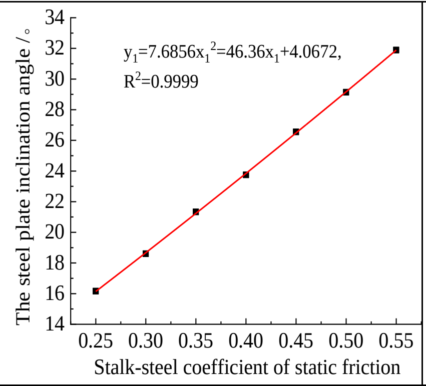


Fig. 6 - The fitting curve of Eq.12

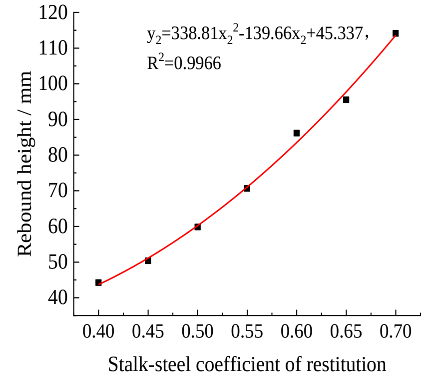


Fig. 7 - The fitting curve of Eq.12

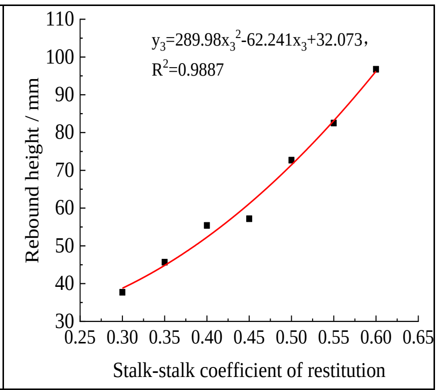


Fig. 8 - The fitting curve of Eq.12

Calibration of contact parameters based on stacking test

It is difficult to measure and calibrate the stalk-stalk CSF, stalk-stalk CRF and the stalk-steel CRF. The measurement error of traditional bench test is large. Stacking angle is a macro parameter to characterize the flow and friction characteristics of discrete materials. During the process of stalk falling and stacking on the surface of steel plate, the value of contact parameter significantly affects the shape of stalk stacking (*Ghodk et al., 2017*). In this section, by analysing and comparing the results of bench stacking test and simulation stacking test, the response surface methodology (RSM) based on central composite design (CCD) was used to calibrate the above three parameters (*Wang et al., 2021*).

The stacking test is shown in Fig. 9. The funnel and steel plate were made of Q235, and the distance between the lower end face of the funnel and the steel plate was 75 mm. The stalk fell freely from the centre of the funnel and accumulated on the surface of steel plate. After all the stalks fell on the steel plate and stood still, using the camera to take the front view picture of the stalk pile, the image was binarized, and the contour curve was extracted by edge detection using MATLAB. The edge points of the contour curve were fitted linearly.

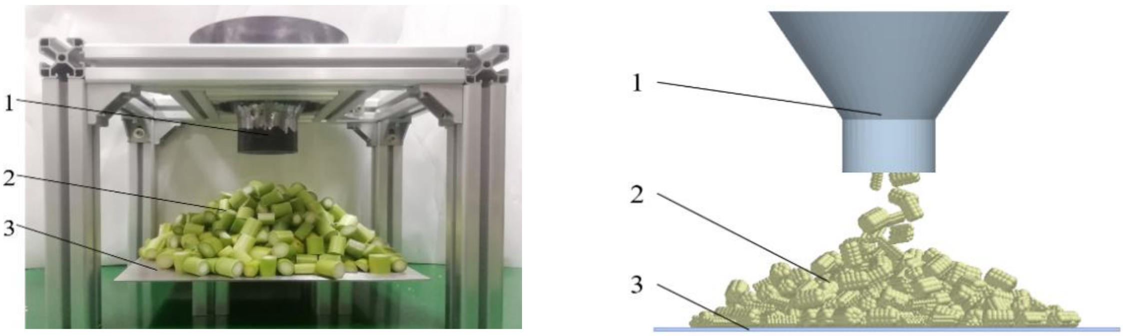
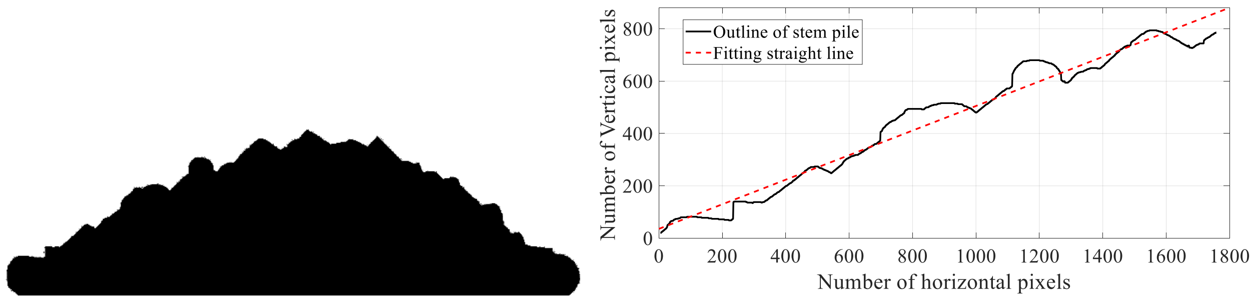


Fig. 9 - Stacking test of KG stalk

1– Funnel; 2– KG stalk; 3– Steel plate

The arctangent value of the slope of the fitting line was calculated, which was the stacking angle. The image processing is shown in Fig. 10. The stacking test was repeated 5 times, and the average value was taken. The measured value of stacking angle of KG stalk was 26.22°.



(a) Binary image (b) Fitting line diagram

Fig. 10 - Image processing of stalk pile

When setting simulation parameters, select the calibrated parameters: μ_1=0.372、e_1=0.656、e_2=0.523. The DEM models of small diameter stalk, medium diameter stalk, large diameter stalk and semi cylindrical stalk were added in EDEM. According to the shape distribution of KG stalk after cutting, the generation rate ratio of four models was set as 6:15:3:7. The stalk-stalk CSF (X_1), stalk-stalk CRF (X_2) and stalk-steel CRF (X_3) were selected as test factors. And the relative error (δ) of simulation test stacking angle (θ') and bench test stacking angle (θ) was taken as test index. The relative error (δ) was calculated according to Eq. 6,

$$\delta = \frac{|\theta' - \theta|}{\theta} \times 100\% \tag{6}$$

The steepest ascent test was used to determine the value range of CCD factors. According to the pre-test results, the stalk-stalk CSF (X_1) ranged from 0.3 to 0.6, the stalk-stalk CRF (X_2) ranged from 0.01 to 0.19, and the stalk-steel CRF (X_3) ranged from 0.05 to 0.35. The steepest ascent test was used to determine the 0 level and optimal value interval of factors for CCD.

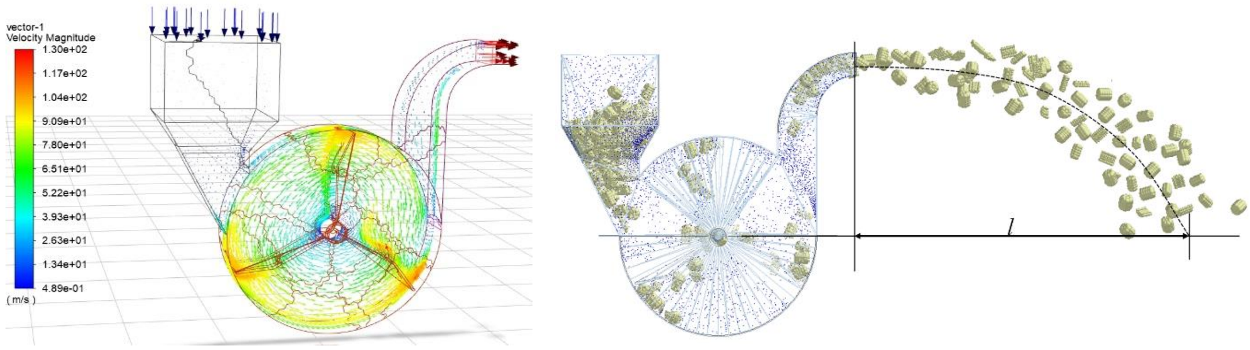
Verification test

After CCD test, in order to further verify the reliability of the DEM model and contact parameters of KG stalk, a stalk throwing test bench was designed for throwing test, and the CFD-DEM coupling simulation throwing test was carried out by using the established DEM model and calibrated contact parameters. Under different rotating speed of throwing plate (400、500、600 and 700 r/min), the trajectory curves of straw throwing in bench test and simulation test were compared, and the relative error of throwing distance was calculated. The throwing test bench of KG stalk was shown in Fig. 11. The funnel was connected with the throwing room, and the stalk in the funnel can enter the throwing room under the action of gravity. A high-speed rotating throwing plate was installed in the throwing room. The throwing plate was powered by a stepping motor. The stalks entering the throwing room were thrown out under the action of the throwing plate. At the beginning of the test, the baffle was inserted into the connection between the funnel and the throwing chamber, and the cut KG stalks were put into the funnel. The frequency converter was adjusted to make the throwing plate reach the speed set in the test. After the speed was stable, the baffle was drawn out to make the stalks enter the throwing room to start the throwing operation. The pictures of the throwing trajectory of the stalks were taken by using the camera (DJI POCKTE 2).

Fig. 11 – Test bed for KG throwing

1– KG stalk; 2– Funnel; 3– Baffle; 4– Throwing chamber; 5– Stepping motor

According to the design dimension of throwing test bench, the 3D model was established by UG NX 8.5. In order to simplify the analysis, the model was imported into ANSYS-SCDM software for preparation. The 3D model was imported into Fluent software. By using Fluent for simulation calculation, the vector distribution of fluid velocity in the throwing room was obtained, as shown in Figure 12a. The 3D of the throwing test bench was imported into EDEM. Particle factory was added in the funnel and the ratio of small diameter stalk, medium diameter stalk, large diameter stalk and semi cylindrical stalk were set as 6:15:3:7. The rotation speed of the throwing plate was set according to the test requirements. Then CFD-DEM coupling simulation throwing test was carried out in EDEM. After the end of the simulation, the simulation throwing trajectory pictures were obtained in the post-processing. The stalk throwing simulation experiment is shown in Fig. 12b.



(a) Velocity vector distribution (b) CFD-DEM coupling simulation throwing test

Fig. 12 – KG stalk Simulation test

RESULTS

Result of steepest ascent test

The steepest ascent test scheme and results are shown in table 5. According to the analysis of table 5, the relative error of simulation test 3 was the smallest. So, test 3 was selected as medium level, test 2 and 4 were selected as low level and high level respectively for CCD test. The low, middle and high levels of each variable were designated as -1, 0 and 1, respectively, and 1.682 is the axial distance from the centre point. The stalk-stalk CSF (X_1), stalk-stalk CRF (X_2) and stalk-steel CRF (X_3) were taken as test factors, the optimization ranges were 0.35 ~ 0.45, 0.04 ~ 0.10 and 0.10 ~ 0.20 respectively.

Table 5

Steepest ascent test scheme and results

Test No.	X_1	X_2	X_3	θ' /°	δ /%
1	0.30	0.01	0.05	18.63	28.93
2	0.35	0.04	0.10	21.58	17.69
3	0.40	0.07	0.15	23.73	9.50
4	0.45	0.10	0.20	29.52	12.58
5	0.50	0.13	0.25	31.49	20.10
6	0.55	0.16	0.30	33.02	25.95
7	0.60	0.19	0.35	34.91	33.16

Result of CCD test

The coding of CCD test factors is shown in Table 6, and the design scheme and results of simulation test are shown in Table 7. The study of RSM and the optimization of results were carried out by using the software Design expert 10.0.7. A quadratic polynomial regression model was assumed for predicting the response. The regression equation of stacking angle relative error (δ) was obtained as:

$$\delta = \text{-}1563.72X_1\text{-}220.42X_2\text{-}744.36X_3\text{-}1661.7X_1X_2 + 637.81X_1X_3 - 1034.73X_2X_3 + 2023.51X_1^2 + 7093.08X_2^2 + 1947.51X_3^2 + 345.77 \tag{7}$$

Table 6

Code table of simulation test factors

Code	X_1	X_2	X_3
-1.628	0.35	0.04	0.10
-1	0.37	0.05	0.12
0	0.40	0.07	0.15
1	0.43	0.09	0.18
1.628	0.45	0.10	0.20

Table 7

Test scheme and results

Test No.	Factor level			Index
	X_1	X_2	X_3	δ /%
1	-1(0.37)	-1(0.05)	-1(0.12)	7.5
2	1(0.43)	-1	-1	11.39
3	-1	1(0.09)	-1	8.96
4	1	1	-1	7.67
5	-1	-1	1(0.18)	9.11
6	1	-1	1	13.6
7	-1	1	1	6.72
8	1	1	1	9.34
9	-1.682(0.35)	0(0.07)	0(0.15)	8.03
10	1.682(0.45)	0	0	10.57
11	0(0.40)	-1.682(0.04)	0	11.4
12	0	1.682(0.10)	0	9.85
13	0	0	-1.682(0.10)	7.35
14	0	0	1.682(0.20)	10.87
15	0	0	0	4.29
16	0	0	0	3.66
17	0	0	0	2.89
18	0	0	0	4.7
19	0	0	0	3.35
20	0	0	0	4.44
21	0	0	0	2.85
22	0	0	0	4.69
23	0	0	0	3.35

The analysis of variance of Eq.7 is shown in Table 8. The quadratic regression model for stacking angle relative error were significant (P < 0.05) and the R^2 were higher than 0.9518. Among these model variables, X_1、X_2、X_1^2、X_2^2 and X_3^2 all had a very significant impact (P < 0.01), X_3 and X_1X_2 both had a significant impact (P<0.05). The effect of X_1X_3 and X_2X_3 on stacking angle error (δ) were not significant. The non-significant factors were eliminated and the optimized quadratic regression model was obtained as Eq. 8

$$\delta = -1468.05X_1 - 375.63X_2 - 561.67X_3 - 1661.7X_1X_2 + 2023.51X_1^2 + 7093.08X_2^2 + 1947.51X_3^2 + 345.77 \quad (8)$$

Through using Design Expert 10.0.7, the influence of the interaction between stalk-stalk CSF X_1 and stalk-stalk CRE X_2 on the relative error of stacking angle can be obtained, and the response surface graph is shown in Figure 13a. It can be seen from Figure 13b that the contour line presents ellipse with larger curvature, and the interaction was significant. When the stalk-stalk CSF is 0.39 ~ 0.41 and the stalk-stalk CRF is 0.06 ~ 0.08, the relative error of stacking angle is small.

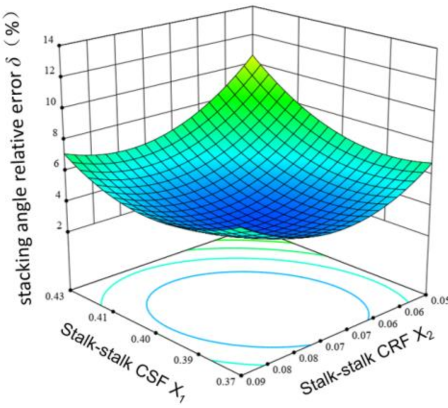
Table 8

Analysis of variance of regression equation

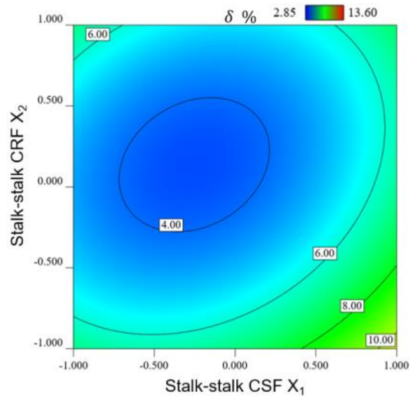
Source	Sum of square	df	Sum of mean square	F-value	P-value
model	217.82	9	24.20	28.51	< 0.0001**
X_1	14.31	1	14.31	16.86	0.0012**
X_2	9.71	1	9.71	11.44	0.0049**

X_3	6.16	1	6.16	7.25	0.0184*
X_1X_2	6.21	1	6.21	7.32	0.0180*
X_1X_3	2.54	1	2.54	3.00	0.1072
X_2X_3	2.41	1	2.41	2.84	0.1159
X_1^2	50.83	1	50.83	59.88	< 0.0001**
X_2^2	80.94	1	80.94	95.35	< 0.0001**
X_3^2	47.08	1	47.08	55.47	< 0.0001**
Residual	11.04	13	0.85		
Lack of fit	6.63	5	1.33	2.41	0.1293
Pure Error	4.41	8	0.55		
Total	228.85	22			

Note: * indicates that this item has significant effect on the result (P≤0.05), * * indicates that this item has extremely significant effect on the result (P≤0.01).



(a) Response surface graph



(b) Contour map

Fig. 13 – Effect of interaction between X_1 and X_2 on relative error of stacking angle

Using the optimization module of Design expert 10.0.7 software, taking the minimum relative error of stacking angle as the objective, the regression equation was solved, the response surface is analysed. The objective and constraint equations were shown as:

$$\begin{cases} \min \delta(X_1, X_2, X_3) \\ s.t. \begin{cases} 0.35 \le X_1 \le 0.45 \\ 0.04 \le X_2 \le 0.10 \\ 0.10 \le X_3 \le 0.20 \end{cases} \end{cases} \tag{9}$$

Through data processing, the optimal parameter combination of regression model was obtained as follows: the stalk-stalk CSF was 0.393, the stalk-stalk CRF was 0.072, the stalk-steel CRF was 0.144. The calibrated contact parameters were substituted into EDEM software for stacking simulation test. The average stacking angle was 26.91° and the relative error with bench test was 2.63%. It showed that the optimal combination of simulated contact parameters was basically consistent with the actual value, which can be used for subsequent simulation test.

Result of verification test

Python was used to process the images of throwing trajectory in bench test and simulation test, and the coordinates of throwing trajectory points were extracted. By using Origin 2018 to fit the coordinate data of trajectory points, the trajectory curves and fitting equations of bench test and simulation test under different throwing speeds were obtained, as shown in Fig. 14. It can be seen that the throwing trajectory curves of the two experiments were relatively consistent. The measured and simulated values of throwing distance of stalk under four throwing speeds (400, 500, 600 and 700 R / min) were shown in table 9 and the relative errors of throwing distance were 3.46%, 8.26%, 8.82% and 10.46% respectively. The above results show that the optimized DEM model and contact parameters can be used in the discrete element simulation experiment, which can provide theoretical support for the follow-up simulation.

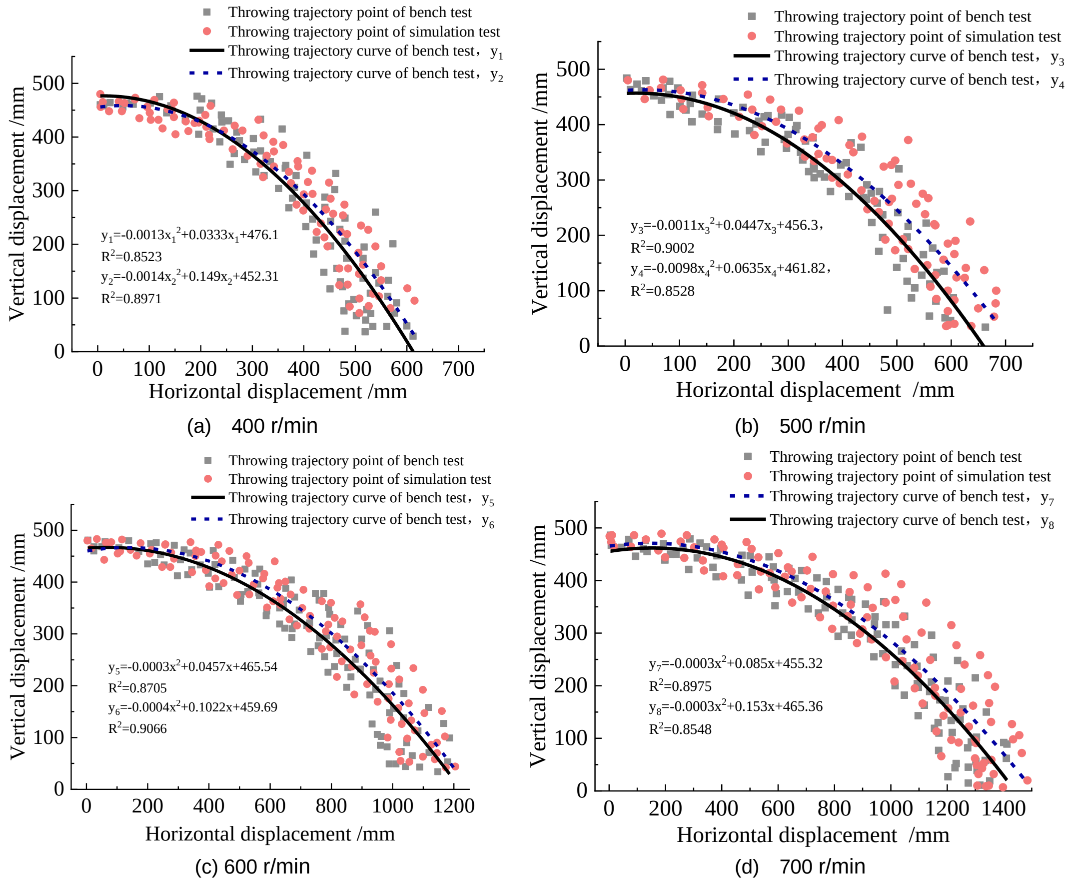


Fig. 14 - Fitting curve of stalk throwing trajectory

Table 9

Scheme and results of verification experiment

Parameters		**Speed [r/min]**			
		400	**500**	**600**	**700**
Distance throwing [mm]	Bench test	603.24	664.70	1324.21	1381.75
	Simulation test	624.10	719.63	1207.35	1526.31
Relative error /%		3.46	8.26	8.82	10.46

CONCLUSIONS

Compared with soil, fertilizer, seeds and other forages, the DEM model of KG stalk is more complex and more difficult to establish and calibrate. In this paper, the parameters of DEM model were calibrated by the combination of bench test and simulation test. Through the slope sliding test between stalk and steel plate, the stalk-steel coefficient of static friction was calibrated as 0.372. Through the collision bounce test between stalk and stalk, stalk and steel plate, the stalk-steel coefficient of restitution and stalk-stalk coefficient of restitution were calibrated as 0.656 and 0.523. Through the stalk stacking test of KG stalk, the actual stacking angle of stalk was measured as 26.22°. Based on the steepest ascent test and CCD test, the optimal values of stalk-stalk coefficient of static friction, stalk-stalk coefficient of rolling friction, stalk-steel coefficient of rolling friction were calibrated as 0.393, 0.072 and 0.144, respectively. In order to verify the accuracy of the model and parameters, the test bench of KG stalk throwing was designed, and the actual and simulation throwing test were carried out. The throwing trajectory curve of the simulation test is consistent with that of the actual test, which verifies the accuracy of the DEM model and contact parameters of KG stalk.

There were differences between the simulation model parameters and the actual parameters, but there was no obvious difference in the test results, which also showed the significance of parameter calibration. This study provides model and parameter support for the application of DEM to study the interaction mechanism between KG stalk and harvester, and provides a stalk DEM model verification method based on throwing test. It is worth noting that this study only established the DEM model of KG stalk, and the leaves will also be affected in the actual harvest. In further research, the DEM model under the mixed state of stalk and leaf should be established.

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