PARAMETER CALIBRATION FOR DISCRETE ELEMENT SIMULATION OF CUTTING DECK CLEANING IN SMALL PLOT WHEAT COMBINE HARVESTER
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小区小麦联合收获机割台清理离散元仿真参数标定

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ABSTRACT

The analysis of the clearing process of the cutting deck of a small plot wheat combine harvester requires the use of discrete element simulation methods. However, the current simulation test lacks the contact parameters such as wheat stalk and stalk-seed. In this paper, the wheat stalks and seeds at harvest time were taken as the research objects, and the calibration study of the discrete element simulation model parameters of stalks and stalk-seeds was carried out by means of mechanical test determination and EDEM software simulation. The stiffness coefficients of wheat stalks were determined by mechanical tests; the average values of wheat stalk stacking angle of 39.22° and wheat stalk-seed stacking angle of 44.41° were obtained by stacking angle tests. By the steepest climb test and binary regression test, the stalk normal stiffness coefficient was determined to be 5e+08N/m2 and tangential stiffness was determined to be 6.35e+08N/m2; the stalk-stalk collision recovery coefficient was obtained to be 0.551, static friction coefficient was obtained to be 0.797, and rolling friction coefficient was obtained to be 0.079 by the two-level analytical factorization test, the steepest climb test, and the three-factor response surface test. Based on this, the average value of wheat stalk-seed stacking angle was obtained to be 39.22° and the average value of wheat stalk-seed stacking angle was obtained to be 44.41° by the stacking angle test. On this basis, the coefficient of recovery of stalk-stalk collision was 0.434, the coefficient of static friction was 0.884, and the coefficient of rolling friction was 0.339 obtained by the three-factor response surface test. Three validation experiments were carried out by substituting the obtained parameters into the simulation test, and the error values were close to the error value %0.255 in the model, which proved that the experimental data were reliable.

摘 要

小区小麦联合收获机割台清理过程的分析需要使用离散元仿真方法。但目前仿真试验缺乏小麦茎秆、茎秆-籽粒等接触参数。本文以收获期的小麦茎秆、籽粒为研究对象，通过力学试验测定和EDEM软件仿真的方式对茎秆和茎秆-籽粒的离散元仿真模型参数展开标定研究。通过力学试验测定了小麦茎秆的刚度系数；通过堆积角试验，得到小麦茎秆堆积角的平均值为 39.22°及小麦茎秆-籽粒堆积角的平均值为 44.41°。通过最陡爬坡试验和二元回归试验，确定了茎秆法向刚度系数为 5e+08N/m2 和切向刚度为 6.35e+08N/m2；通过二水平析因试验、最陡爬坡试验和三因素响应曲面试验获得了茎秆-茎秆的碰撞恢复系数为 0.551、静摩擦系数为 0.797、滚动摩擦系数为 0.079；在此基础上，通过三因素曲面响应试验获得了茎秆-籽粒的碰撞恢复系数为 0.434、静摩擦系数为 0.884、滚动摩擦系数为 0.339。将得到参数代入仿真试验中进行三次验证实验，误差值接近模型中的误差值%0.255，证明试验数据可靠。

INTRODUCTION

When the small plot wheat combine harvester works, it is required to realize no material residue, and to solve the problem of material residue on the cutting platform of the combine harvester, it is necessary to study the movement law of wheat harvesting material in the combine harvester *(Li., 2022)*, and to establish a more accurate discrete element simulation model.

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The discrete element method is a numerical simulation method that can accurately describe the discontinuous nature of the flow of material particles *(Carr et al., 2023)*, so as to reveal the internal mechanism of action and shorten the research period. When discrete element simulation is carried out, the relevant parameters are usually obtained by means of direct measurement method and virtual calibration, and for some parameters that are difficult to be measured directly, they need to be obtained by means of calibration *(Liu et al., 2021).* The soybean intrinsic parameters as well as the contact parameters between soybean and seed expeller were calibrated by Tao Zhang et al. *Li Jinguang et al*. obtained the mechanical property parameters of the main root system of spinach by compression test, and derived the normal and tangential stiffness coefficients of the root system *(Dai et al., 2023)*. Ucgul et al. integrated the linear adhesion cohesive model into the linear Hysteretic Spring model to obtain the soil static friction factor, rolling friction factor and recovery coefficient similar to the actual angle of repose *(Ucgul et al., 2014)*. Fanyi et al. proposed a nonlinear contact model based on DEMeter++ software to characterize the plastic characteristics between stems, but it could not characterize the viscosity effects of stems with different compression degrees *(Fanyi et al., 2018)*. Thakur et al. proposed the Edinburgh Elasto-Plastic Adhesion (EEPA) contact model, which is based on Hertz's contact theory and extends to include the elastoplastic and viscous properties of the particle contact model *(Thakur et al., 2014)*. Park et al. measured the angle of repose and the number of remaining particles of garlic particles experimentally, and derived the friction factor between particles by using the swing arm method *(Park et al., 2021)*.

In this paper, the wheat stalks in harvest season were taken as the research object, and EDEM simulation software was used as the test platform. By using the loading force obtained in the three-point bending physical test of the stalk as the reference value, the test was conducted in EDEM with the loading force in the three-point bending simulation as the target value *(Wang et al., 2021)*. The factor intervals were narrowed down by the steepest climb test, and then the normal/tangential stiffness coefficients of the stalks were obtained by binary regression test *(Ni et al., 2022)*; the stacking angle of the stalk particles was obtained by the stalk particle cylinder lifting test, and with this as the target value the two-level analytical factorization test based on the cylinder lifting test, the steepest climb test, and the three-factor response surface test were carried out in the EDEM, and the factors influencing the stacking angle and the contact parameters between the stalks; the stacking angle of the mixture was obtained by performing cylinder lifting test on the stalk and seed mixture *(Li et al., 2021)*, and a three-factor surface response test was conducted with this objective value to obtain the contact parameters between the stalks and the seeds. This study provides basic parameters for the discrete element simulation study of wheat harvesting, and provides a modelling method and parameter calibration method for the discrete element simulation analysis of the material motion process of the cutting platform.

MATERIALS AND METHODS

Determination of parameters

- **Wheat stem eigen parameters**

Selected the wheat at the crown of the year as the experimental subject, and volume of leaves shrinked due to lossing of water during the harvesting process but this shrinkage had litte impact on the experiment results, so leaves were removed during the experiment. After measuring 300 stalks by vernier callipers, the mean length was 632.32 mm, the standard deviation of length was 8.23, the mean diameter was 4.45 mm, the standard deviation of diameter was 1.07; and the mean density of stalks was 1.642 g/cm by overflow method.

- **Three-point bending physical tests**

The mechanical properties of wheat stalks have a large impact on the operational performance of harvesting machinery. In order to establish the discrete elemental model of the wheat cutter harvester at a later stage, it is necessary to know the normal and tangential stiffness of the wheat stalk. Therefore, the three-point bending test was chosen to determine the loading pressure of the stalk under 0.5 mm bending deflection, and then the three-point bending test was simulated in EDEM at a later stage to explore the loading force under the same bending deflection, and when the loading force is the same, the normal and tangential stiffness of the wheat stalks can be obtained.

In order to generalize the data collected to represent the relevant physical characteristics of the wheat plant, a sample of 10 wheat stalks with strong growth was used for the selection prior to the three-point bending test. The stalks were measured and the diameter and cross-sectional area were calculated.

Test process: the three-point bending device support frame is fixed to the universal test bench under the fixture, the indenter is fixed to the fixture on the test bench, adjust the spacing of the support frame for 150mm, the upper indenter will be lowered to the lower fixture above the 5 mm (leaving the width occupied by the diameter of the stalks) .The stalks are loaded at a speed of 10mm/min for 2min, and the computer will record the experimental data automatically. The experiment is conducted ten times and get the average loading force 6.91N.

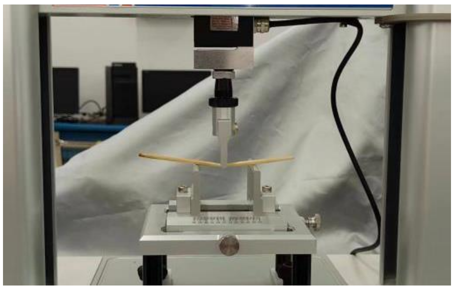

Fig. 1 - Three-point bending physical test

- **Angle of accumulation of stalks**

Wheat stalk stacking angle is the cone of stacking of stalk segments of 20 mm length in the natural state, which is an important indicator of the friction between materials and provides basic data for stalk discrete element modelling *(Tong et al., 2023)*.

The cylinder lifting method was used to measure the stacking angle of the stem samples in this study. Test method: a hollow cylinder with the top and bottom removed was placed on the test bench, the stalk sample was slowly injected into the cylinder from the top of the cylinder, and then the cylinder was rapidly lifted vertically upward so that the stalks naturally collapsed into a conical shape under the action of gravity to form the stacking angle, which was then measured using a protractor *(Liao et al., 2020)*. The test was carried out 10 times, and the average value of the particle stacking angle of stalks and seeds was obtained as 39.08°.

- **Angle of accumulation of stalk-seed mixtures**

The stacking angle of stalk-seed was obtained by using a mixed stacking of stalk particles and seeds, and the stalk-seed contact parameters were solved using the stacking angle as the target value.

Test: The stalks were cut into small segments of 20 mm in length, and the number of samples of small segments of stalks was 100. Bran and impurities were removed from the seeds and 200 g of wheat seeds were weighed. The seeds and stalks were thoroughly mixed in a dry beaker and poured into a hollow cylinder, which was quickly lifted vertically upwards, and the mixed pile rapidly collapsed into a cone *(Gao., 2019)*. The test was conducted 10 times and the average value of stacking angle was obtained as 44.63°. The test procedure is shown in Fig.2.

(a) Angle of wheat stalk accumulation

(b) Accumulation angle of mixed materials between wheat grains and wheat straw

Fig. 2 - Material accumulation angle test

SIMULATION MODEL

Simulation model of three-point bending of stem

Due to the bending deformation of the wheat stalk during the downward pressure by the pivot wheel during harvesting, it is necessary to model the wheat stalk as a flexible body by adopting the Hertz-Mindlin (no slip) and Bonding model, and the particles in the model of the wheat stalk are connected by Bonding bonds, which gives the model flexible body qualities by inputting the appropriate normal and tangential stiffness coefficients. The model is made flexible by inputting appropriate normal and tangential stiffness coefficients.

Create a three-point bracket model in Solid Works, export it to *stl* format and then import it into EDEM software *(Liu., 2021)*, set the particle radius to 0.5 mm, the contact radius to 0.62 mm, the stem length to 250 mm, and the stem radius to 4.25 mm. Set up the particle factory on the left side of the cylinder's circular surface, adjust the gravity to the negative direction of the lateral X-axis so that the particles are moving to the right side, and fill the particles as 5000, generating 2500 particles per second, and the generation is completed in 1 second. Set the bond key to be generated at 1.1 s, and make the loading column move downward at a uniform speed at 1.2 s, the loading speed of the loading column is 10 mm/s, the loading time is 4 s, and the total time of simulation is 5.2 s.

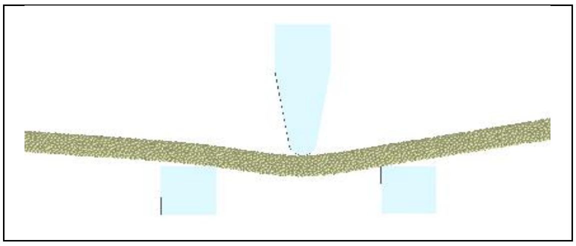

Fig. 3 - Three-point bending simulation test process

Simulation modelling of stem particle stacking angle

In EDEM, the Hertz-Mindlin model is selected for the wheat stalk cylinder lifting simulation test, as a way to calculate the force and motion process between wheat stalk and stalk, and decompose the force and motion process between wheat stalk particles into normal motion, tangential motion and rolling motion *(Wang et al., 2021)*. The wheat stalks are in cylinder shape, so several spherical particles were put together in one direction to get the closest physical experiment situation, see fig 5, and radius of the spherical particle is set to 2.15mm, so that nine combined spherical particles could become a 20mm approximate cylinder and then use this kind of combined spherical particles to conduct pile angle simulation experiment and simulate how the wheat stalks pile under cylinder lifting experiment. Combined with the simulation parameters of the wheat material in the discrete element simulation, the range of variation of the simulation parameters in this study was determined as shown in Table 1.

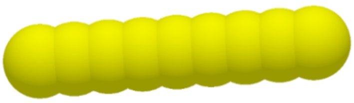

Fig. 4 - Wheat stalk granular pattern

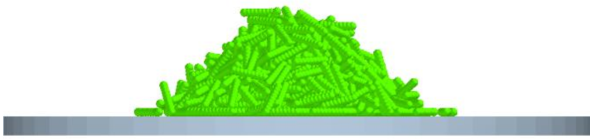

Fig. 5 - Simulation test of stem particle cylinder lifting

Table 1

Simulation parameter value list

Simulation parameters	numerical value
Stem density/(kg/m^3)	1642a
Stem Poisson's ratio	0.4b
Stem shear modulus/MPa	5.52e+06a
Density of steel/(kg/m^3)	7810b
Poisson's ratio of steel	0.3b
Steel shear modulus/MPa	2.07e+11b
Stalk-stalk collision recovery coefficient x_1	0.1-0.4c
Coefficient of static friction of stalk-stalk x_2	0.3-0.5c
Coefficient of rolling friction of stalk-stalk x_3	0.05-0.15c
Stem-steel collision recovery coefficient x_4	0.3-0.7c
Static friction coefficient of stem-steel x_5	0.14-0.20c
Rolling friction coefficient of stem-steel x_6	0.05-0.15c

Note: Item a is determined experimentally, item b is obtained from the literature, and item c is the experimental variable, the range of which is the upper and lower limits of the value of the variable, the same as below.

Simulation model of stalk-seed mixture stacking angle

The Hertz-Mindlin model was used to model the seed particles. As shown in Fig.6, the seed grain models were all simplified to elliptical shapes to improve the simulation efficiency.

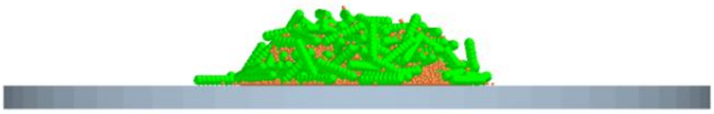

Fig. 6 - Cylinder lifting test of soil and stem mixed materials

Table 2

Parameter List of Cylinder Lifting Simulation Test for Straw and grains Mixed Materials

Simulation parameters	Numerical value
Stalk density/(kg/m^3)	1642
stem Poisson's ratio	0.4
Stem shear modulus/MPa	5.52e+06
Density of steel/(kg/m^3)	7810
Poisson's ratio of steel	0.3
Steel shear modulus/MPa	2.07e+11
Stalk-stalk collision recovery coefficients	0.551
Coefficient of static friction of stalk-stalk	0.797
Coefficient of rolling friction of stalk-stalk	0.079
Collision recovery coefficients for stalk-steel	0.5
Static friction coefficient of stalk-steel	0.7
Rolling friction coefficient of stalk-steel	0.1
Stalk-seed collision recovery coefficient x_7	0.3-0.7
Static friction coefficient of stalk-seed x_8	0.5-0.9
Rolling friction coefficient of stalk-seed x_9	0.3-0.6

Some of the parameters in the table have been obtained by investigating the literature, physical tests, and stalk stacking calibration tests, but the collision recovery coefficients of stalk-seed x_7, static friction coefficients of stalk-seed x_8, and rolling friction coefficients of stalk-seed x_9 are still lacking, so the range intervals in which the values are located were determined by reviewing the literature, and then the specific values were obtained by calibrating them.

RESULTS

Stem stiffness coefficient calibration

(1) Selection of test factor level range: According to the existing research on wheat stalks, there is no exact value for the stiffness coefficient of wheat stalks, which is due to the different varieties of the samples used and the differences between the individuals of the samples used; therefore, this study combines the data of the previous researchers, and determines the normal stiffness value of wheat stalks, x_{10} , and the tangential stiffness value of wheat stalks, x_{11} , between 1e+ 08N/m2 to 1.1e+09N/m2 .

Table 3

Test factor level

level (of	1	2	3	4	5	6
numerical	1e+08	3e+08	5e+08	7e+08	9e+08	1.1e+09

(2) Steepest Climbing Test: Since x_{10} and x_{11} are stiffness coefficients, the loading force is bound to increase with the increase of stiffness coefficients, so design the stiffness coefficients incrementally, and record and observe the error value between the loading force and the loading force in the physical test *(Yuan et al., 2020)*.

The steepest climb test design and results are shown in Table 4, from which it can be seen that as the stiffness factor increases, the relative error value of the loading force compared to the physical test results decreases and then increases, so the optimum value of the stiffness factor should be between the test parameters of the 3rd and 4th sets of tests.

Table 4

Design and results of the steepest climbing test

serial number	x10	x11	Loading force (N)	relative error
1	1e+08	1e+08	0.493	27.82%
2	3e+08	3e+08	0.567	16.98%
3	5e+08	5e+08	0.635	7.03%
4	7e+08	7e+08	0.712	4.25%
5	9e+08	9e+08	0.793	16.11%
6	1.1e+09	1.1e+09	0.879	28.7%

(3) Binary regression test: from the results of the steepest climbing test data, the range of stiffness coefficient is narrowed from 1e+08N/m^2 to 1.1e+0.9N/m2 to 5e+08N/m^2 to 7e+08N/m^2, in order to obtain the specific value of the stiffness coefficient, the corresponding functional relationship between the stiffness coefficient and loading force is obtained through the two-factor, three-level binary regression test and then the specific value is obtained through the inverse function. In order to obtain the specific value of the stiffness coefficient, the corresponding functional relationship between the stiffness coefficient and loading force was obtained by two-factor three-level binary regression test. The test design and results are shown in Table 5.

Table 5

Design and results of a binary regression experiment

Test number	x_{10}	x_{11}	error value
1	-1	-1	3.03
2	1	-1	1.28
3	-1	1	0.3
4	1	1	7.03
5	-r	0	1.11
6	r	0	3.93
7	0	-r	2.24
8	0	r	3.67
9	0	0	0.18
10	0	0	0.19
11	0	0	0.2
12	0	0	0.19
13	0	0	0.19

The two-factor, three-level binary regression simulation test conducted to solve the wheat stem stiffness coefficient was analysed by ANOVA as shown in Table 6, and the P-value of the model was <0.0001, indicating that the model had a good fit. The P-values of the two main terms x_{10} and x_{11} are <0.0001, indicating that the two main terms are significant. The interaction term $x_{10}x_{11}$ has a p-value <0.0001 and the interaction term is significant. P-value for both squared terms x_{10}^2 and x_{11}^2 < 0.0001 indicating that both squared terms are significant.

Table 6

Analysis of variance in binary regression tests

items	square sum (e.g. equation of squares)	(number of) degrees of freedom (physics)	mean square and	P-value	F-value
mould	52.74	5	10.55	240.42	<0.0001
x_{10}	10.05	1	10.05	229.14	<0.0001
x_{11}	3.18	1	3.18	72.44	<0.0001
$x_{11}x_{12}$	17.98	1	17.98	409.75	<0.0001
x_{10}^2	10.15	1	10.15	231.42	<0.0001
x_{11}^2	14.14	1	14.14	322.25	<0.0001
pure error	0.0002	4	0.0001		

The regression equation for the actual value was obtained through a binary regression test:

$$R_1 = 160.8172 - 2.6097x_{10} - 2.9197x_{11} + 2.12x_{10}x_{11} + 1.2081x_{10}^2 + 1.4256x_{11}^2 \quad (1)$$

The minimum value of the function is found to be 0.07, when x10 is 5e+08N/m² and x11 is 6.35e+08N/m².

Calibration of stalk-stalk contact parameters

For discrete element simulation of wheat harvesting, the stalk-seed contact parameter needs to be input, but this parameter is difficult to obtain directly, and the stalk-seed contact parameter can be obtained by subjecting the mixture material of stalks and seeds to a calibration test based on the lifting of discrete element cylinders. However, the stalk-to-stalk contact parameter is needed for the stacking simulation test of the mixture material, so the stacking calibration test of the stalk particles needs to be performed first. The test index is the stacking angle, the value of the angle is measured by physical test and the angle measured by physical test is used as the target value in the calibration test *(Zhang et al., 2023)*.

(1) Two level factorial test: the basic contact parameters affecting the stacking angle of stalk particles in the test included six factors: collision recovery coefficient of stalk-stalk x_1 , static friction coefficient of stalk-stalk x_2 , rolling friction coefficient of stalk-stalk x_3 , collision recovery coefficient of stalk-steel x_4 , static friction coefficient of stalk-steel x_5 , rolling friction coefficient of stalk-steel x_6 , and the factors were ranked in order of significance by the two-level factorial test.

The contribution of the factors and whether they were significant or not was determined by a two-level analytic factorization test. The simulation test factors and levels are shown in Table 7 and the simulation test design and results are shown in Table 8.

Table 7

Factors and level selection of two-level factorial test

Considerations	**Level (of achievement etc.)**	
	-1	**1**
Stalk-stalk collision recovery coefficient x_1	0.3	0.7
Coefficient of static friction of stalk-stalk x_2	0.5	0.9
Coefficient of rolling friction of stalk-stalk x_3	0.05	0.15
Stem-steel collision recovery coefficient x_4	0.3	0.7
Static friction coefficient of stem-steel x_5	0.5	0.9
Rolling friction coefficient of stem-steel x_6	0.05	0.15

Table 8

Two-level factorial experimental design and results

Serial number	**x_1**	**x_2**	**x_3**	**x_4**	**x_5**	**x_6**	**Stacking angle (°)**
1	0.3	0.5	0.05	0.3	0.5	0.05	39.43
2	0.7	0.5	0.05	0.3	0.9	0.05	36.09
3	0.3	0.9	0.05	0.3	0.9	0.15	43.31
4	0.7	0.9	0.05	0.3	0.5	0.15	42.71
5	0.3	0.5	0.15	0.3	0.9	0.15	42.21
6	0.7	0.5	0.15	0.3	0.5	0.15	42.4
7	0.3	0.9	0.15	0.3	0.5	0.05	46.93
8	0.7	0.9	0.15	0.3	0.9	0.05	41.16
9	0.3	0.5	0.05	0.7	0.5	0.15	38.01
10	0.7	0.5	0.05	0.7	0.9	0.15	33.69
11	0.3	0.9	0.05	0.7	0.9	0.05	51.80
12	0.7	0.9	0.05	0.7	0.5	0.05	36.12
13	0.3	0.5	0.15	0.7	0.9	0.05	45.47
14	0.7	0.5	0.15	0.7	0.5	0.05	47.46
15	0.3	0.9	0.15	0.7	0.5	0.15	44.40
16	0.7	0.9	0.15	0.7	0.9	0.15	48.01

Table 9 was obtained through the analysis function that comes with the Design-Expert software, from which the significant degree of the effect of each test factor on the stalk accumulation angle can be obtained, and the order of the influence of each factor on the wheat stalk accumulation angle from the largest to the smallest is as follows: the rolling friction coefficient of stalk-stalk x_3, the static friction coefficient of stalk-stalk x_2, the collision recovery coefficient of stalk-stalk x_1 , collision recovery coefficient of stalk-steel x_4, rolling friction coefficient of stalk-steel x_6, and static friction coefficient of stalk-steel x_5, among which, collision recovery coefficient of stalk-steel x_4, rolling friction coefficient of stalk-steel x_6, and static friction coefficient of stalk-steel x_5 had lower influence rates of 1.97%, 1.62%, and 0.31%, respectively.

Table 9

Significance Analysis of Parameters in Two Level Factorial Test

Parameters	Effect	Mean square	Impact rate / %	Order of significance
x1	-2.99	35.76	9.8	3
x2	3.71	55.06	15.08	2
x3	4.61	85.01	23.29	1
x4	1.34	7.18	1.97	4
x5	0.54	1.14	0.31	6
x6	-1.22	5.9	1.62	5

(2) Steepest-climbing test: the steepest-climbing test can quickly narrow down the range of values of the test factors and improve the accuracy of the regression model established by the response surface test *(Zhang et al., 2023)*. The significant factors affecting the stacking angle of wheat stalks were rolling friction coefficient of stalk-stalk x_3, static friction coefficient of stalk-stalk x_2, and collision recovery coefficient of stalk-stalk x_1, with the value ranges of 0.05-0.15, 0.5-0.9, and 0.3-0.7, respectively, and equated to five gradients for the steepest-climbing test, whereas the collision recovery coefficient of stalk-steel x_4, the stalk-steel static friction coefficient x_5, and rolling friction coefficient x_6 of stalk-steel do not have a significant effect on the test results, so the intermediate values are taken directly during the test *(Hongcheng et al., 2022)*, which are x_4 (0.5), x_5 (0.7), and x_6 (0.1), respectively.

The design of the steepest climb test and the results of the test are shown in Table 10, the optimum value should be in the vicinity of the 3rd group of tests, and the range of the selection of the factors was set between the 2nd and 4th groups, x_1 (0.4 to 0.6), x_2 (0.6 to 0.8), and x_3 (0.075 to 0.125).

Table 10

Design and results of the steepest climbing test

Serial number	1	x2	x3	Stacking angle θ_{stalk} / (°)	Relative error $\delta_{\theta stalk}$ / %
1	0.3	0.5	0.05	45.19	15.63%
2	0.4	0.6	0.075	34.24	12.38%
3	0.5	0.7	0.1	37.12	5.02%
4	0.6	0.8	0.125	43.05	10.24%
5	0.7	0.9	0.15	45.79	17.17%

(3) Three-factor surface response test: According to the two-level analytical factorization test, the significant factors affecting the stalk-stalk stacking angle were determined to be the collision recovery coefficient of stalk-steel x_4 , the static friction coefficient of stalk-steel x_5 , and the rolling friction coefficient of stalk-steel x_6 , and the range of values of the factors were determined to be based on the results of the steepest-climbing test), x_2 (low level 0.6, zero level 0.7, high level 0.8), x_3 (low level 0.075, zero level 0.1, high level 0.125). The experiment was conducted 17 times and the experimental design and results are shown in Table 11.

Table 11

Three factor response surface experimental design and results

Serial number	x1	x2	x3	Stacking angle θ_{stalk}/°	Relative error $\delta_{\theta stalk}$ / %
1	0.4	0.6	0.1	42.18	7.93
2	0.6	0.6	0.1	46.85	19.88
3	0.4	0.8	0.1	43.57	11.49
4	0.6	0.8	0.1	40.12	2.66

Serial number	x1	x2	x3	Stacking angle θ_{stalk}/°	Relative error $\delta_{\theta stalk}$ / %
5	0.4	0.7	0.075	41.56	6.35
6	0.6	0.7	0.075	41.59	6.42
7	0.4	0.7	0.125	44.23	13.18
8	0.6	0.7	0.125	44.59	14.1
9	0.5	0.6	0.075	45.93	17.53
10	0.5	0.8	0.075	37.63	3.71
11	0.5	0.6	0.125	42.65	9.14
12	0.5	0.8	0.125	45.66	16.84
13	0.5	0.7	0.1	42.96	9.93
14	0.5	0.7	0.1	43.10	10.29
15	0.5	0.7	0.1	43.36	10.95
16	0.5	0.7	0.1	42.86	9.67
17	0.5	0.7	0.1	43.02	10.08

The ANOVA of the simulation test is shown in Table 12, the P-value of the model <0.0001 indicates that the model has a good fit; the P-value of x_1 is 0.04, the P-value of both x_2 and x_3 is <0.0001, and the P-values of the three main terms are less than 0.05, which indicates that the three main terms are significant; the P-values of the interaction terms, x_1x_2, and x_2x_3 are less than 0.05, which indicates that they are significant, and the P-value of the squared term, x_1x_3 P-value of x_1x_3 is 0.4756 indicating that it is not significant; P-value of squared terms x_{12} and x_{22} is more than 0.5 indicating that it is not significant and P-value of squared term x_{32} is less than 0.5 indicating that it is significant.

Table 12

Analysis of variance in three factor response surface test

Source of variance	degrees of freedom	mean square	F	P
mould	9	8.51	177.66	<0.0001
x_1	1	0.32	6.76	0.04
x_2	1	14.12	294.77	<0.0001
x_3	1	13.57	238.24	<0.0001
x_1x_2	1	16.48	344.00	<0.0001
x_1x_3	1	0.03	0.57	0.4756
x_2x_3	1	31.98	667.37	<0.0001
x_{12}	1	0.02	0.46	0.5186
x_{22}	1	0.01	0.20	0.6696
x_{32}	1	0.08	1.72	0.2308
residual	7	0.05		
lost proposal	3	0.06	1.79	0.2883
pure error	4	0.04		
aggregate	16			

The optimized regression equation is based on ensuring that the model is significant and the out-of-fit term is not significant, and removing the insignificant terms:

$$\theta_{\mathrm{stalk}} = 52.19 + 144.11x_1 - 24.89x_2 - 696.93x_3 - 203x_1x_2 + 1131x_2x_3 - 213.33x_3^2 \tag{2}$$

Through the regression equation obtained from the above test, it is difficult to get directly the values of x_1, x_2, x_3 respectively under the target value obtained from the physical test, so the stacking angle error value for the target value is analysed for the corresponding surface analysis, and the equation obtained is as follows:

$$\delta_{\theta \text{stalk}} = 30.34 + 434.61x_1 - 127.07x_2 - 1635.61x_3 - 519.5x_1x_2 + 85x_1x_3 + 2152x_2x_3 - 74.33x_1^2 + 104.93x_2^2 + 914.8x_3^2 \quad (3)$$

Taking the stacking angle as a function of 39.08°, the stalk-stalk contact parameters were obtained as: x_1 =0.551, x_2 =0.797, x_3 =0.079, at which time the error δ_θ was 0.255%.

Stem stacking angle validation test

The optimal parameter solutions obtained after optimization of the three-factor surface response design test were substituted into the EDEM simulation model for simulation validation test. The simulation parameters were set as follows: the collision recovery coefficient of stalk-stalk was 0.551, the static friction coefficient of stalk-stalk was 0.797, and the rolling friction coefficient of stalk-stalk was 0.079, and all other non-significant factors were taken to be the middle of the corresponding range of factors. The validation test was conducted three times and the mean value of stacking angle was obtained as 39.22°, at which point the error value was 0.358%. It is close to the error value of 0.255% in the model, indicating that the test data are reliable.

Calibration of stalk-seed contact parameters

(1) Parameter setting: the contact parameters between the stalks have been obtained through the study in the previous section and hence the parameters have been set in the table below for the cylinder lifting simulation tests on the stalk-seed mixtures:

Table 13

Parameter List of Cylinder Lifting Simulation Test for Straw and Soil Mixed Materials

Simulation parameters	Numerical value
Stalk density/(kg/m^3)	1642
Stem Poisson's ratio	0.4
Stem shear modulus/MPa	5.52e+06
Density of steel/(kg/m^3)	7810
Poisson's ratio of steel	0.3
Steel shear modulus/MPa	2.07e+11
Stalk-stalk collision recovery coefficients	0.551
Coefficient of static friction of stalk-stalk	0.797
Coefficient of rolling friction of stalk-stalk	0.079
Collision recovery coefficients for stalk-steel	0.5
Static friction coefficient of stalk-steel	0.7
Rolling friction coefficient of stalk-steel	0.1
Stalk-seed collision recovery coefficient x_7	0.3-0.7
Static friction coefficient of stalk-seed x_8	0.5-0.9
Rolling friction coefficient of stalk-seed x_9	0.3-0.6

Some of the parameters in the table have been obtained by investigating the literature, physical tests, and stalk stacking calibration tests, but the collision recovery coefficient of stalk-seed x_7 , the static friction coefficient of stalk-seed x_8 , and the rolling friction coefficient of stalk-seed x_9 are still lacking, therefore, in combination with the relevant parameters obtained in the previous section, the range interval in which the values are located is determined by consulting the literature, and then the specific values are obtained by calibration.

(2) Three-factor surface response test: Design-Expert software was used to design the three-factor surface response test and establish the regression model, and the test design and results are shown in Table 14.

Table 14

Three factor and three level experimental design and results

Serial number	x_7	x_8	x_9	stacking angle $\theta_{\text{Stalks - Seeds}}$/°	relative error $\delta_{\theta \text{Stalks - Seeds}}$ / %
1	0.3	0.7	0.6	44.82	0.43
2	0.5	0.7	0.45	43.63	2.24

Serial number	x_7	x_8	x_9	stacking angle $\theta_{Stalks-Seeds}$/°	relative error $\delta_{\theta Stalks-Seeds}$ / %
3	0.5	0.9	0.6	45.47	1.88
4	0.3	0.5	0.45	43.03	3.59
5	0.5	0.7	0.45	43.66	2.17
6	0.7	0.5	0.45	41.53	6.95
7	0.5	0.5	0.3	41.85	6.23
8	0.5	0.7	0.45	43.81	1.84
9	0.7	0.9	0.45	44.19	0.99
10	0.5	0.9	0.3	44.23	0.9
11	0.3	0.7	0.3	43.83	1.79
12	0.7	0.7	0.3	42.19	5.47
13	0.5	0.7	0.45	43.81	1.84
14	0.7	0.7	0.6	43.42	2.71
15	0.3	0.9	0.45	45.68	2.35
16	0.5	0.5	0.6	42.78	4.15
17	0.5	0.7	0.45	43.81	1.84

The response surface test was conducted and the test results were fitted by Design-Expert software, and the coefficient of determination R^2 of the model was obtained to be 0.9980, which indicated a high degree of fit; the fitted regression model was:

$$\theta_{\text{st al k-seed}} = 43.74 - 0.7538x_7 + 1.3x_8 + 0.5488x_9 + 0.0025x_7x_8 + 0.06x_7x_9 + 0.0775x_8x_9 - 0.077x_7^2 - 0.0595x_8^2 - 0.102x_9^2 \quad (4)$$

The analysis of variance (ANOVA) of the simulation test is shown in Table 14, the P-values of x_7, x_8, and x_9 are <0.0001, indicating that the three main terms are significant; the P-values of the interaction terms $x_7 x_8$, $x_7 x_9$, and $x_8 x_9$ are greater than 0.05, indicating that the interaction terms are insignificant; the P-values of the squared terms x_8^2 and x_9^2 are greater than 0.05, indicating that the two squared terms are insignificant, and the P-values of the squared term x_7^2 are smaller than 0.05, indicating that it is significant; after removing the insignificant terms the regression equation of the optimized model is obtained as:

$$\theta_{\text{st al k-seed}} = 43.68 - 0.7538x_7 + 1.3x_8 + 0.5488x_9 - 0.1096x_9^2 \quad (5)$$

Table 14

Analysis of variance in three factor and three level experiments

Source of variance	Degrees of freedom	Mean square	F	P
mould	9	2.28	390.43	<0.0001
x_7	1	4.55	777.04	<0.0001
x_8	1	13.47	2302.51	<0.0001
x_9	1	2.41	411.85	<0.0001
x_7x_8	1	0	0.0043	0.9497
x_7x_9	1	0.0144	2.46	0.1606
x_8x_9	1	0.024	4.11	0.0823
x_7^2	1	0.025	4.27	0.0777
x_8^2	1	0.0149	2.55	0.1544
x_9^2	1	0.0438	7.49	0.0291
residual	7	0.0058		
lost proposal	3	0.0026	0.3150	0.8151
pure error	4	0.0083		
aggregate	16			

Through the regression equation obtained from the above test, it is difficult to get directly what values of x_7, x_8, x_9 respectively under the target value obtained from the physical test, so the stacking angle error value for the target value is analysed for the corresponding surface analysis, and the equation obtained is as follows:

$$\delta_{\theta stalk\text{-}seed} = 38.6 - 2.79x_7 + 7.38x_8 + 4.93x_9 + 0.06x_7x_8 + 2x_7x_9 + 2.58x_8x_9 - 1.93x_7^2 - 1.49x_8^2 - 4.53x_9^2 \quad (6)$$

Taking the stacking angle as a function of 44.63°, the stem-seed contact parameters were obtained as follows: x_7 =0.434, x_8 =0.884, x_9 =0.339, at which point the error was 0.255%.

Stalk-seed stacking angle validation test

The optimal parameter solutions obtained from the optimization of the three-factor surface response design test were substituted into the simulation model for the simulation verification test. The simulation parameters were set as follows: the collision recovery coefficient of stalk-seed was 0.434, the static friction coefficient of stalk-seed was 0.884, the rolling friction coefficient of stalk-seed was 0.339, and the other insignificant factors were taken to be the middle of the corresponding range. The validation test was carried out three times and the mean value of the stacking angle of the stalk-seed mixture was obtained as 44.41°, at which point the error value was 0.493%. It is close to the error value of 0.255% in the model, indicating that the experimental data are reliable.

CONCLUSIONS

(1) The intrinsic parameters of wheat stalks were measured using harvested wheat plants as the study object. The intrinsic parameters of wheat stalks were obtained. The discrete elemental model of wheat stalk and seed was developed based on the combination of literature review and measured eigen-parameters using Hertz-Mindlin model and Hertz-Mindlin with bonding model.

(2) Physical tests were carried out on wheat stalks and seeds and by calibrating these parameters, normal stiffness of 5e+08N/m2 and tangential stiffness of 6.35e+08N/m2 were obtained for wheat stalks.

(3)The average value of the stacking angle obtained from the physical test in the stalk-stalk stacking angle validation test is 39.22°, and the simulation parameters of stalk-stalk are determined after the validation of the simulation test, the collision recovery coefficient is 0.551, the static friction coefficient is 0.797, and the rolling friction coefficient is 0.079, and the average value of the stacking angle of the stalk-seed cylindrical lifting simulation experiment is 44.41°. With these parameters, it can be verified that the collision recovery coefficient of stalk-seed grain is 0.434, static friction coefficient is 0.884 and rolling friction coefficient is 0.339.

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