Calibration of discrete element simulation parameters and threshing test for complete wheat plants

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Abstract: The existing discrete element model of wheat plants lacks the glume, which hinders the simulation of the entire threshing process. To address this issue, this paper takes wheat at the harvest stage as the research object and constructs a complete discrete element model of wheat plants with glumes based on the Hertz-Mindlin with bonding model in the EDEM simulation software. The parameter calibration of wheat glumes discrete element model is studied through collision bounce experiments, slope experiments, and accumulation experiments. The results show that the coefficient of restitution, coefficient of static friction, and coefficient of rolling friction between glume and steel are 0.488, 0.625, and 0.048, respectively, and the coefficient of restitution, coefficient of static friction, and coefficient of rolling friction between glume and glume are 0.232, 0.966, and 0.059, respectively. The relative errors between the simulation results and the measured values are less than 5%, and the calibration parameters are effective. Based on the structural parameters of the self-developed experiment-bed of tangential axial-flow grain threshing device, a three-dimensional model of the wheat threshing device is established to simulate the whole threshing process of the complete wheat plant, and the bench-scale experiments are carried out with the non-threshing rate as the performance index. The results indicate that the model can completely simulate the separation process of glume and grain and the movement law of different grains, and the relative error of non-threshing rate between the simulation experiments and bench-scale experiments is 4.36%. This further demonstrates that the proposed model can provide a reference for the wheat threshing process research and device performance optimization design.

Keywords: discrete element method, wheat plant, glume model, parameter calibration, threshing experiments
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1 Introduction

Threshing is one of the important links in the process of mechanized wheat harvesting, and its performance directly affects the operation quality of the combine harvester. At present, it is of great guiding significance to study the movement law of wheat plants in threshing device to improve threshing performance, so it is very important to establish a comprehensive and complete wheat plant model[1].

The discrete element method can effectively solve the numerical simulation problem of discontinuous media, and has been widely used in the field of agricultural engineering[2-4]. Currently, the EDEM discrete element simulation software is the most widely used in the threshing of wheat, corn, and other grains. The API method and particle aggregation method to establish the discrete element model of wheat plants have been widely studied[5-9] . Still, these models lack the glume part and cannot simulate the separation process of glume and grain in wheat threshing. The wheat plant is mainly composed of four parts: grain, glume, spike shaft, and stem. The separation of glume and grain is the key factor to determine the performance index of the threshing device, so the structure and performance of glume have great influence on the simulation effect of wheat plant discrete element model[10]. At the same time, in order to ensure the accuracy of discrete element simulation experiments, the parameters of the established material model need to be calibrated in the software. Material parameters mainly include intrinsic parameters and contact parameters. Intrinsic parameters are the characteristic parameters of materials themselves, which are usually measured by physical experiments and verified in software[11-13]. Contact parameters are characteristic parameters when two materials interact with each other. Usually, the optimal parameter values are obtained by combining the actual experiments and simulation experiments, and calibrating based on optimization methods such as steep slope experiments and orthogonal regression combination experiments[14-18].

In this paper, a discrete element model of complete wheat plant with glume is constructed by reverse modeling method, and the parameters required for glume in the simulation process are calibrated by combining actual experiments and simulation experiments. The whole process of wheat threshing is simulated with the tangential flow threshing device as the model, and the separation process of the glume and the grain and the movement law of different grains are analyzed. The bench-scale experiments are carried out with the non-threshing rate as the performance index, providing a new basis and method for the optimal design and research of threshing devices.

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2 Establishment of discrete element model of complete wheat plant

2.1 Model parameters

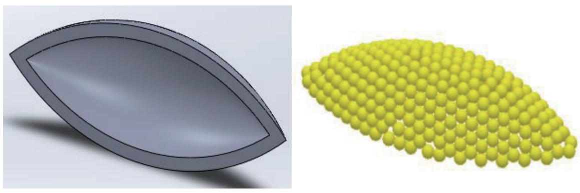
In this paper, Zhengmai 1860, a plant with large and full grains, no ear axis damage and some stems at harvest time, is selected as a modeling reference. This wheat variety is one of the main varieties in Henan Province at present, with an average 1000-grain weight of 48.5 g and a moisture content of 15% at harvest time. The parameters of each part of the wheat are measured, and the average value is taken as the shape and size criterion of the discrete element model. In order to reduce the simulation time and error accumulation during threshing, all plants are generated with the same data. The parameters are listed in Table 1.

Table 1 Discrete element model parameters of wheat plants

Material	Basic structure	Parameter
Stem	Slender cylinder	Length 200 mm, diameter 5 mm
Spike shaft	Slender cylinder	Length 66 mm, diameter 3 mm
Glume	Thin-walled elliptic shell	Length 10 mm, maximum width 4 mm, maximum height 4 mm, wall thickness 0.2 mm
Grain	Elliptic-like entities	Length 6.8 mm, maximum width 3 mm, maximum height 2.3 mm

2.2 Modeling

In the actual threshing process, the glume is rarely crushed when it is impacted, squeezed, and rubbed by threshing elements. Usually it splits in the middle and then falls off directly from the grain. Therefore, a half glume is selected as the basic unit to model in Solidwork software, and the 3D model of its outline is shown in Figure 1a. The model of half glume profile is imported into EDEM software, and it is created by spherical particle aggregation method. The number of particles required to complete half glume is 280, and its discrete element model is shown in Figure 1b.



a. 3D model b. Discrete element model

Figure 1 Glume model

The structure of wheat stem and spike shaft is simple, and the stress and fracture in the actual threshing process are also relatively easy. Considering that the grains are only peeled off during threshing and rarely broken, the stem, spike shaft, and grains can be directly modeled by spherical particle aggregation and bond connection in EDEM software. The stem consists of 40 spherical particles, the spike shaft consists of 33 spherical particles, a single grain consists of eight spherical particles, and each wheat plant contains 28 grains with glumes. The position of the wheat ear on the spike shaft is adjusted and determined with Meta-Partical function, and the connection of all components is realized by adding the Hertz-Mindlin with bonding contact model between particles. After combining the stem, spike shaft, glume, and grain, the complete wheat plant discrete element model is shown in Figure 2.

Figure 2 Discrete element model of complete wheat plant

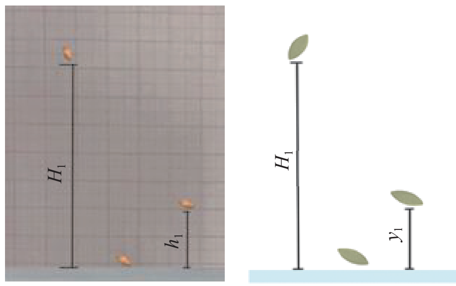
3 Contact parameter calibration

In the experiment-bed of threshing device designed in the early stage, the materials of threshing elements and drum are all made of Q235 steel, so the contact parameters between glume and Q235 steel and between glumes are calibrated in this paper. Contact parameters include coefficient of restitution, coefficient of static friction, and coefficient of rolling friction, and commonly used calibration experiments include collision bounce experiments, slope experiments, and accumulation experiments[19-21].

3.1 Calibration of contact parameters between glume and Q235 steel

3.1.1 Coefficient of restitution

Coefficient of restitution is generally measured by collision bounce experiments. In a relatively enclosed environment, the intact glume with grain is allowed to fall freely from the height H_1= 100 mm and collided with Q235 steel plate, and the maximum bouncing height h of glume is recorded by a high-speed camera, as shown in Figure 3a. The experiments are repeated for five times to obtain the average value, and the maximum bounce height h_1= 23.04 mm when the glume collides with the steel plate is measured. According to the same experiment conditions in EDEM software, the simulation experiments are carried out with the maximum bounce height y_1 as the performance index and the coefficient of restitution x_1 as the single factor, as shown in Figure 3b.



a. Physical experiments b. Simulation experiments

Figure 3 Calibration experiments of coefficient of restitution

The range of x_1 is set to 0.40-0.60. Five groups of single factor experiments are conducted with a step size of 0.05, and each group of experiments is repeated five times to take the average value. The experiment results are listed in Table 2.

Table 2 Simulation experiment data of coefficient of restitution

Serial No.	x_1	y_1/mm
1	0.40	18.22
2	0.45	22.83
3	0.50	27.14
4	0.55	31.96
5	0.60	37.57

The experimental data in Table 2 is fitted, and the fitting curve is obtained as shown in Figure 4. The curve equation is as follows:

$$y_1 = 71.714x_1^2+23.946x_1-2.716$$

The equation determining coefficient is 0.9975, indicating that the fitting reliability of the equation is extremely high. Substituting the maximum bounce height of 23.04 mm in the physical experiments into the equation, x_1=0.488 is obtained. Substituting it into the EDEM software, the confirmatory collision and bounce experiments are carried out. The experiments are repeated five times to take the average value, and the maximum bounce height of 23.91 mm of the simulation experiments is obtained, with a relative error of 3.77%. Therefore, the coefficient of restitution between glume and Q235 steel is 0.488.

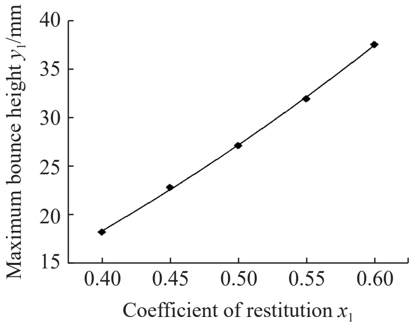
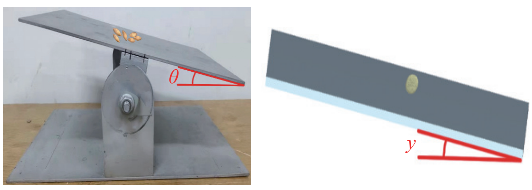


Figure 4 Fitting curve of coefficient of restitution and maximum bounce height in simulation experiments

3.1.2 Coefficient of static friction and coefficient of rolling friction

Coefficient of static friction and coefficient of rolling friction are generally measured by slope experiments. When measuring the coefficient of static friction, in order to ensure that the material slides first instead of rolling, the material is placed longitudinally on a Q235 steel plate. When measuring the coefficient of rolling friction, in order to ensure that the material rolls first instead of sliding, the material is placed horizontally on the Q235 steel plate. In order to avoid contingency, a suitable number of complete glumes with grains are selected for physical experiments, and the critical inclination angle θ of steel plate when the first glume begins to slide (roll) is measured with a digital display angle ruler, as shown in Figure 5a. The average value is calculated by repeating the same experiment conditions for five times, and the measured value of the critical inclination angle of the steel plate during sliding, θ_1=32.48°, is obtained, and the measured value of the critical inclination angle of the steel plate during rolling, θ_2=2.78°, is obtained. In the EDEM software, under the same experiment conditions, the critical inclination angles y_2 and y_3 of steel plates are taken as performance indicators, and the coefficient of static friction x_2 and coefficient of rolling friction x_3 are taken as single factors, as shown in Figure 5b.



a. Physical experiments b. Simulation experiments

Figure 5 Calibration experiments of coefficient of friction

The range of x_2 is set to 0.50-0.70, five groups of single factor experiments are conducted with a step size of 0.05, and each group of experiments is repeated five times to take the average value. The experiment results are listed in Table 3.

Table 3 Simulation experiment data of coefficient of static friction

Serial No.	x_2	y_2/(°)
1	0.50	27.87
2	0.55	30.04
3	0.60	32.15
4	0.65	33.52
5	0.70	36.54

The experimental data in Table 3 is fitted, and the fitting curve is obtained as shown in Figure 6. The curve equation is as follows:

$$y_2 = 25.714x_2^2+10.429x_2+15.922$$

The equation determining coefficient is 0.9907, and the fitting reliability is extremely high. Substituting the measured average inclination angle of 32.48° in the physical experiments into the equation, x_2=0.625 is obtained. Substituting it into EDEM software, the slope experiments of the confirmatory coefficient of static friction are carried out. The average value is calculated by repeating the same experiment conditions for five times, and the critical inclination angle of the simulation experiment steel plate 32.13° is obtained, with a relative error of 1.07%. Therefore, the coefficient of static friction between glume and Q235 steel is 0.625.

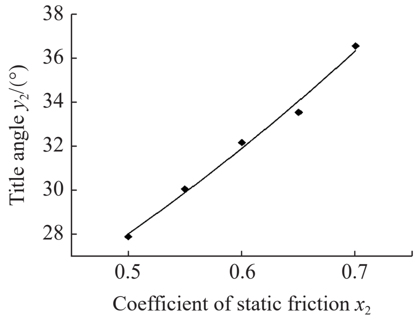


Figure 6 Fitting curve of coefficient of static friction and critical inclination angle in simulation experiments

The range of x_3 is set to 0.03-0.05, five groups of single factor experiments are conducted with a step size of 0.005, and each group of experiments is repeated five times to take the average value. The experiment results are listed in Table 4.

Table 4 Simulation experiment data of coefficient of rolling friction

Serial No.	x_3	y_3/(°)
1	0.030	1.70
2	0.035	1.96
3	0.040	2.35
4	0.045	2.72
5	0.050	2.97

The experimental data in Table 4 is fitted, and the fitting curve is obtained as shown in Figure 7. The curve equation is as follows:

$$y_3 = -79.365x_2^2+61.349x_2+0.0187$$

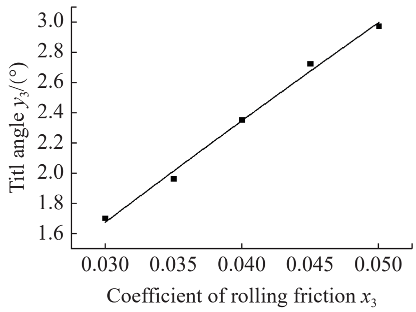


Figure 7 Fitting curve of coefficient of rolling friction and critical inclination angle in simulation experiments

The equation determining coefficient is 0.9943, and the fitting reliability is extremely high. Substituting the measured average tilt angle of 2.78° in the physical experiments into the equation, x_3=0.048 is obtained. Substituting it into EDEM software, the slope experiments of the confirmatory coefficient of rolling friction are carried out. The average value is calculated by repeating the same experiment conditions for five times, and the critical inclination angle of the simulation experiment steel plate 2.69° is obtained, with a relative error of 3.23%. Therefore, the coefficient of static friction between glume and Q235 steel is 0.048.

3.2 Calibration of contact parameters between glume and glume

3.2.1 Physical experiment

Accumulation angle is a macroscopic parameter representing the material flow and friction characteristics, and three basic contact parameters can be calibrated through accumulation experiments. According to the requirements of the accumulation experiments, a half-intact glume after peeling grain is selected as the specimen. An appropriate number of glumes are selected, and the physical experiment process is shown in Figure 8a. The one-sided image of glume accumulation is processed by Matlab software, and the binary image is obtained as shown in Figure 8b. Based on the same experiment conditions, the experiments are repeated five times to obtain the average value, and the measured value of glume accumulation angle of γ=22.86° is obtained.

a. Experiment process b. Experiment result

Figure 8 Accumulation physical experiments

3.2.2 Simulation experiment

(1) Steep slope experiment

Considering that there is a positive correlation among coefficient of restitution X_1, coefficient of static friction X_2, and coefficient of rolling friction X_3 between glumes, steep slope experiments are carried out under the same experiment conditions in EDEM software, with accumulation angle y as the performance index and X_1, X_2, and X_3 as experiment factors. The experiment process is shown in Figure 9a, and the binary image is shown in Figure 9b.

a. Experiment process b. Experiment result

Figure 9 Accumulation simulation experiments

Five groups of simulation experiments are carried out by choosing appropriate step size, and each group of experiments is repeated five times to calculate the average value. The factor level and performance index data of the five groups of experiments are listed in Table 5, where Y is the relative error between the accumulation angle y and the accumulation angle γ of the physical experiments.

The optimal value range is near the factor level of group B, and the factor levels of groups A, B, and C are selected as the –1, 0, and 1 levels of the three-factor quadratic orthogonal regression combination experiments.

Table 5 Factor level and performance index of simulation steep slope experiments for accumulation angle

Serial No.	X_1	X_2	X_3	y/(°)	Y/(%)
A	0.20	0.85	0.055	22.11	3.28
B	0.25	0.90	0.060	22.39	2.06
C	0.30	0.95	0.065	23.69	3.63
D	0.35	1.00	0.070	24.21	5.91
E	0.40	1.05	0.075	24.93	9.06

(2) Orthogonal regression combination experiment

According to the same experiment conditions in EDEM software, taking the relative error Y between the accumulation angle of the simulation experiments and accumulation angle of the physical experiments as the performance index, and taking the coefficient of restitution X_1, coefficient of static friction X_2, and coefficient of rolling friction X_3 as the experiment factors, the orthogonal regression combination experiments are carried out, and the experiment factor codes are listed in Table 6.

Table 6 Coding of factors for orthogonal regression combination experiments of accumulation angle simulation

Code	X_1	X_2	X_3
–1.682	0.20	0.85	0.055
–1	0.22	0.89	0.057
0	0.25	0.95	0.060
1	0.28	1.01	0.063
1.682	0.30	1.05	0.065

There are eight groups of orthogonal experiments and 15 groups of regression experiments, with each experiment repeated five times to calculate the average value. The experiment scheme and results are listed in Table 7, where A, B, and C represent the coefficient of restitution, coefficient of static friction, and coefficient of rolling friction, respectively.

Table 7 Experiment scheme and results of orthogonal regression combination for accumulation angle simulation

Serial No.	A	B	C	Y/(%)
1	1	1	1	2.95
2	1	1	–1	2.01
3	1	–1	1	1.57
4	1	–1	–1	3.76
5	–1	1	1	1.43
6	–1	1	–1	2.16
7	–1	–1	1	3.22
8	–1	–1	–1	3.32
9	1.682	0	0	0.90
10	–1.682	0	0	1.28
11	0	1.682	0	0.39
12	0	–1.682	0	3.23
13	0	0	1.682	0.41
14	0	0	–1.682	1.57
15	0	0	0	1.49
16	0	0	0	2.45
17	0	0	0	0.70
18	0	0	0	1.49
19	0	0	0	2.45
20	0	0	0	0.70
21	0	0	0	0.70
22	0	0	0	1.49
23	0	0	0	0.70

With Design-Expert 13 software, multiple regression fitting is performed on the experiment data in Table 7, and the regression equation for the relative error Y of the accumulation angle is obtained as follows:

$$Y = 1.33 - 0.03A - 0.59B - 0.29C + 0.32AB - 0.05AC + 0.31BC + 0.18A^2 + 0.42B^2 + 0.13C^2$$

The equation determining coefficient is 0.94, and the fitting reliability is high. The results of variance analysis on the regression equation are listed in Table 8.

Table 8 Analysis of variance of regression equation

Source of variance	Sum of squares	Degrees of freedom	Mean square	F	p
Model	11.18	9	1.24	1.38	0. 002891
A-A	0.0168	1	0.0168	0.0187	0.001 934
B-B	4.80	1	4.80	5.33	0.000 380
C-C	1.19	1	1.19	1.32	0.002 709
AB	0.8321	1	0.8321	0.9248	0.003 538
AC	0.0221	1	0.0221	0.0245	0.008 780
BC	0.7813	1	0.7813	0.8683	0.003 684
A^2	0.4506	1	0.4506	0.5008	0.004 917
B^2	2.84	1	2.84	3.16	0.000 989
C^2	0.2812	1	0.2812	0.3126	0.005 856
Residual	11.70	13	0.8997		
Lack of fit	7.53	5	1.51	2.89	0.1882
Pure error	4.17	8	0.5211		
Cor total	22.88	22			

The results indicate that the coefficient of restitution, coefficient of static friction, coefficient of rolling friction, and interaction term all have an impact on the relative error of repose angle, and there is a quadratic relationship between indicators and factors, rather than a simple linear relationship. The factors that affected the relative error of repose angle, in descending order, are coefficient of static friction, coefficient of restitution, and coefficient of rolling friction, and the lack of fit is not significant, indicating that there are no other main factors affecting the indicators.

3.2.3 Optimal parameters

Using the optimization module of Design-Expert 13 software, with the objective of minimizing the relative error of the accumulation angle, the regression equation is solved and the response surface is analyzed, and the optimal factor level range is obtained as follows:

$$0.220 \leq X_1 \leq 0.279,\ 0.891 \leq X_2 \leq 1.009,\ 0.057 \leq X_3 \leq 0.063$$

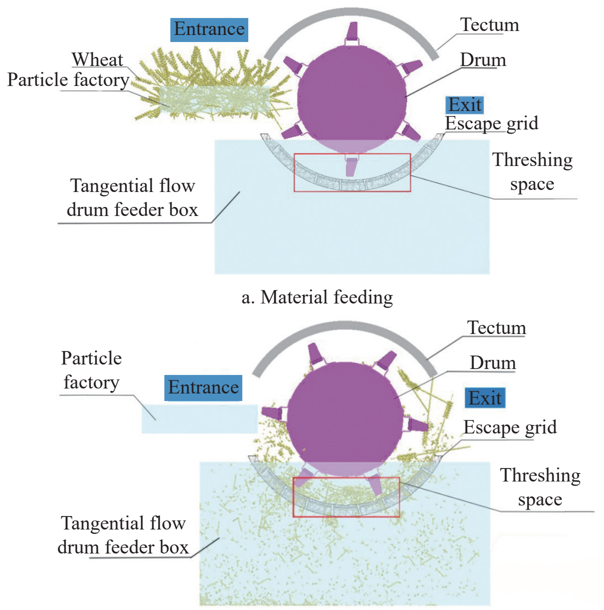
Based on the model presented in this article, a verification experiment of accumulation simulation is conducted with a coefficient of restitution of 0.232, a coefficient of static friction of 0.966, and a coefficient of rolling friction of 0.059 between the glumes. Repeating the calculation of the average value for five times, the simulation accumulation angle is 22.69°, which showed high similarity with the results of the physical experiments in terms of angle and shape, with a relative error of only 0.74%. This shows that the optimal parameters have excellent reliability.

4 Simulation of whole process of wheat threshing

The self-developed experiment-bed of tangential axial-flow grain threshing device is used as a model for simulation. The designed feed rate is 12 kg/s, the diameter of tangential drum is 576 mm, the length is 1280 mm, and the experiment speed ranges from 500 to 700 r/min. The threshing elements are in the shape of plate teeth with a height of 50 mm, symmetrically distributed in six columns on the master wire of the threshing cylinder.

4.1 Threshing process of mixed materials

Combining EDEM software and the characteristics of the discrete element model of complete wheat plants established in this paper, 100 wheat plants are initially generated by the simulation method adapted to a feeding rate of 12 kg/s, and enter the threshing device at an initial speed of 8 m/s, as shown in Figure 10a. According to the actual motion characteristics of the threshing cylinder, the rotation speed of the threshing cylinder is set to 600 r/min in the simulation experiments. Combined with the number of particles and physical characteristics of this model, the time stepping is set to 2.5×10^{-6} s, and the simulation time is a total of 0.5 s. The simulation process can effectively simulate the movement, interaction, and separation process of materials in the threshing device, as shown in Figure 10b.



a. Material feeding

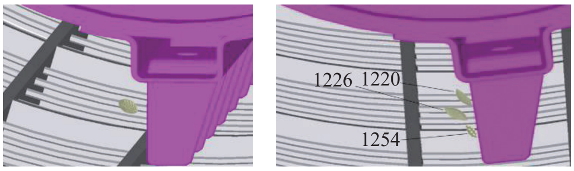
b.Threshing process

Figure 10 Threshing simulation experiments of complete wheat plant

From the simulation experiments, it can be seen that without considering the crushing, after the wheat plants enter the tangential threshing device at a given initial speed, they follow the threshing drum to make irregular circular motion with random delay, and there are irregular small radial and axial reciprocating translations in the threshing space composed of the drum and the upper and lower shells. After continuous collision, extrusion, and rubbing with the threshing drum, upper and lower shells, and threshing plate teeth, the complete wheat plants become intertwined mixed materials. After threshing, the grains and a small amount of impurities fall into the tangential receiving box through the concave screen, and most of the impurities are discharged from the discharge port along the tangential direction.

4.2 Analysis of movement process of glumes and grains

In the simulation process, three typical particles representing the two halves of glume and the grain wrapped by them are selected for analysis, with particle numbers 1220, 1226, and 1254, respectively. The separation process of glume and grain is shown in Figure 11. The speed changes of the three particles are shown in Figure 12



a. Before separation b. After separation

Figure 11 Separation process of glume and grain

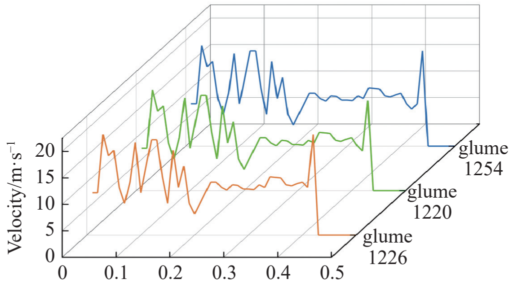


Figure 12 Speed variation diagram of glume and grain

As can be seen from Figure 12, in the initial stage, plants enter the threshing device from the conveyor belt at a uniform speed of 8 m/s, and the movement of the three particles is the same. After about 0.01 s, the particles enter the threshing device together and rotate around the axis with the drum, and the speed is increased to 18 m/s, which is basically consistent with the linear speed of threshing elements. Subsequently, the particles undergo irregular circular motion within the threshing area, resulting in a decrease in the speed and fluctuations in a certain range due to relative sliding and friction resistance. At 0.4 s, the three particles separate and move to the escape grid, and the grain falls first. Glume 1 and glume 2 are wrapped in impurities for a short time and then fall separately. Due to the influence of air resistance, their falling speed is slightly slower than that of the grain.

4.3 Analysis of movement processes of different grains

There are some differences in actual wheat plants, and the movement of materials during threshing exhibits diversity and individuality. However, if random particles are used to generate materials in the discrete element model, the simulation time is too long due to excessive calculation. In this paper, the structure and size of the wheat plants generated during the feeding stage of the simulation process are completely consistent. In order to verify whether the materials have similar characteristics in the simulation process and in the actual movement process, five grains numbered 1254, 1367, 1586, 1662, and 1832 are selected for analysis, and their speed changes are shown in Figure 13.

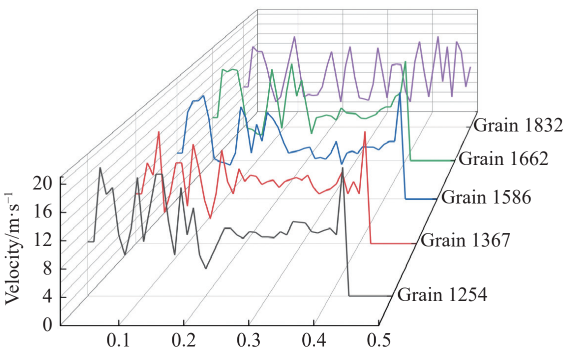


Figure 13 Speed variation diagram of different grains

As can be seen from Figure 13, the four grains numbered 1254, 1367, 1586, and 1662 have similar movement rules, which can be divided into feeding period, pre-movement period, post-movement period, and falling period. During the feeding period, the grains enter the threshing device, the speed increases rapidly under the action of high-speed rotation of the drum, and then the speed decreases due to relative sliding and friction with the threshing element and the casing. In the pre-movement period, the grain speed oscillates up and down obviously, and in the post-movement period, the grain speed fluctuates slightly and tends to be stable. In the falling stage, the grain speed quickly reaches the maximum, leaving the threshing device to fall freely, and the final speed becomes zero (not within the speed measuring range). Although the changing trend is consistent, there are significant differences in numerical performance, high discriminability, and good randomness.

The feeding period and pre-movement period of grain No. 1832 are not much different from the other grains, and the speed change in the post-movement period is still significant, which cannot be stabilized, indicating that it is retained in the threshing device.

4.4 Bench experiment verification

Non-threshing rate is a commonly used index to measure the performance of wheat threshing devices. In the simulation experiments, the bond between glumes remains unchanged when the grains are not released from glumes. By highlighting the bond between glumes, the number of grains with glumes can be accurately calculated and the rate of non-threshing can be obtained, as shown in Figure 14.

Figure 14 Calculation of non-threshing rate by simulation experiments

The wheat threshing bench-scale experiments are carried out under the conditions of 12 kg/s feed rate and 600 r/min tangential cylinder speed, as shown in Figure 15. The average value is calculated by repeating the experiments for five times, and the non-threshing rate of wheat threshing bench-scale experiments is 8.25%.

a. Experiment device b. Experiment results

Figure 15 Threshing bench-scale experiments

The simulation experiments of wheat threshing are carried out under the same parameter conditions, and the average value is calculated by repeating the experiments for five times. It is found that the non-threshing rate of wheat threshing simulation experiments is 7.89%. The relative error between the simulation experiment results and the bench experiment results is 4.36%, which indicates that the complete wheat plant discrete element model established in this paper can be used in discrete element simulation experiments.

5 Conclusions

(1) Combining with 3D modeling software, and based on spherical particle aggregation and bonding contact in EDEM software, a discrete element model of the complete wheat plant including stem, spike shaft, glume, and grain is established, which is highly consistent with the actual wheat plant structure.

(2) The parameters of the discrete element model of wheat glume are calibrated by collision bounce experiments, slope experiments, and accumulation experiments. The coefficient of restitution, coefficient of static friction, and coefficient of rolling friction between glume and Q235 steel are 0.488, 0.625, and 0.048, respectively. The coefficient of restitution, coefficient of static friction, and coefficient of rolling friction between glume and glume are 0.232, 0.966, and 0.059, respectively, and the relative errors between the simulation results and the measured values are less than 3%, indicating that the parameter calibration is effective.

(3) The whole process simulation of wheat threshing is realized based on the self-developed experiment-bed of tangential axial-flow grain threshing device. The separation process of glume and grain in threshing device and the movement change law of different grains are analyzed by selecting typical grains. Based on the performance indicator of non-threshing rate, a bench experiment is conducted to verify the reliability of the discrete element model, with a relative error of 4.36%.

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[References]

[1] Fu H, Wang C R, Jin C, Yu J Q. Research on a modeling method for mature wheat plants. Journal of Northeast Normal University, 2017; 49(2): 69–75. (in Chinese)

[2] Yu Q X, Liu Y, Chen X B, Sun K, Lai Q H. Calibration and experiment of simulation parameters for panax notoginseng seeds based on DEM. Transactions of the CSAM, 2020; 51(2): 123–131. (in Chinese)

[3] Cui T, Jing M S, Zhang D X, Yang L, He X T, Wang Z D. Construction of the discrete element model for maize ears and verification of threshing simulation. Transactions of the CSAE, 2023; 39(24): 33–46. (in Chinese) DOI: 10.11975/j.issn. 1002-6819.202307199.

[4] Jia H L, Deng J Y, Deng Y L, Chen T Y, Wang G, Sun Z J, et al. Contact parameter analysis and calibration in discrete element simulation of rice straw. Int J Agric & Biol Eng, 2021; 14(4): 72–81. DOI: 10.25165/j. ijabe.20211404. 6435.

[5] Li X K, Han Z S, DAI F, Gao A M, Wei L J. Simulation research on working parameters of threshing device on plot-bred wheat based on EDEM. Agricultural Research in the Arid Areas, 2016; 34(4): 292–298. (in Chinese) DOI: 10.7606/j. issn.1000-7601.2016.04.44.

[6] Wang W Z, Liu W R, Yuan L H, Qu Z, Zhang H M, Zhou Z. Calibration of discrete element parameters of wheat plants at harvest period based on EDEM. Journal of Henan Agricultural University, 2021; 55(1): 64–72. (in Chinese) DOI: 10.16445/j.cnki.1000-2340. 20210122.014.

[7] Dai F, Song X F, Zhao W Y, Han Z S, Zhang F W, Zhang S L. Motion simulation and test on threshed grains in tapered threshing and transmission device for plot wheat breeding based on CFD-DEM. Int J Agric & Biol Eng, 2019; 12(1): 66–73.

[8] Yuan J B, Wang J F, Li H, Qi X D, Wang Y J, Li C. Optimization of the cylindrical sieves for separating threshed rice mixture using EDEM. Int J Agric & Biol Eng, 2022; 15(2): 236–247.

[9] Dai F, Song X F, Shi R J, Guo W J, Zhai Y M, Wang F, et al. Movement law of the threshing material in threshing and cleaning machine for plot-bred wheat. Int J Agric & Biol Eng, 2022; 15(3): 100–106. DOI: 10. 25165/j.ijabe.20221503. 7194.

[10] Sun Q H, Li G Y, Wang Y, Xu Z X, Yang C, Li G L, et al. Research situation and prospect of rice and wheat breeding harvesters. Agricultural Engineering, 2020; 10(3): 7–11. (in Chinese)

[11] Adajar J B, Alfaro M, Chen Y, Zeng Z W. Calibration of discrete element parameters of crop residues and their interfaces with soil. Computers and Electronics in Agriculture, 2021; 188: 106–113. DOI: 10.1016/j.compag. 2021. 106349.

[12] Schramm M, Tekeste M Z. Wheat straw direct shear simulation using discrete element method of fibrous bonded model. Biosystems Engineering, 2022; 396: 1–12.

[13] Zhang Z G, Zeng C, Xing Z Y, Xun P, Guo Q F, Shi R M, et al. Discrete element modeling and parameter calibration of safflower biomechanical properties. Int J Agric & Biol Eng, 2024; 17(2): 37–46. DOI: 10.25165/ j.ijabe. 20241702.8857.

[14] Hao J J, Wei W B, Huang P C, Qing J H, Zhao J G. Calibration and experimental verification of discrete element parameters of oil sunflower seeds. Transactions of the CSAE, 2021; 37(12): 36–44. (in Chinese)

[15] Chen L, Yu N H, Wang L Z, Fan J J, Lei G, Liu X P, et al. Measurement of contact parameters and discrete element simulation calibration of rice bran and broken rice. Journal of Agricultural Science and Technology, 2024; 26(2): 127–136. (in Chinese)

[16] Liang R Q, Chen X G, Zhang B C, Wang X Z, Kan Z, Meng H W. Calibration and test of the contact parameters for chopped cotton stems based on discrete element method. Int J Agric & Biol Eng, 2022; 15(5): 1–8.

[17] Zhang X J, Wang H T, Wang F Y, Lian Z G. Parameter calibration of discrete element model for alfalfa seeds based on EDEM simulation experiments. Int J Agric & Biol Eng, 2024; 17(3): 33–38. DOI: 10.25165/ j.ijabe.20241703. 8681.

[18] Xie K T, Zhang Z G, Wang F, Yu X L, Wang C L, Jiang S F. Calibration and experimental verification of discrete element parameters of Panax notoginseng root. Int J Agric & Biol Eng, 2024; 17(4): 13–23.

[19] Zhu K, Hui Y B, Zhou Y, Wang H X, Zhang Y L, Li H, et al. Construction of Wheat Grain Model and Calibration of Discrete Element Paramaters Based on X-Ray Tomography. Journal of the Chinese Cereals and Oils Association, 2022; 37(9): 218–223. (in Chinese)

[20] Zhang W L, Wu W B, Lv S J, Wang X F, Jia H P, Liu P K, et al. Experimental calibration of wheat mechanical parameters and contact parameters in milling. Journal of Henan University of Technology, 2023; 44(2): 105–112. (in Chinese)

[21] Liu F Y, Zhang J, Chen J. Modeling of flexible wheat straw by discrete element method and its parameters calibration. Int J Agric & Biol Eng, 2018; 11(3): 42–46.