CALIBRATION AND OPTIMIZATION OF DISCRETE ELEMENT PARAMETERS FOR COTTON STALK-RUBBER BELTS INTERACTIONS
/
棉秆-橡胶带相互作用的离散元参数标定与优化

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DOI: https://doi.org/10.35633/inmateh-75-75

***Keywords:** Discrete element, Cotton stalks, Rubber belts, Parameter calibration, Harvesting efficiency*

ABSTRACT
This study aims to accurately calibrate the interaction between cotton stalks and rubber belts in agricultural machinery using the Discrete Element Method (DEM). Through physical experiments, key parameters such as the collision recovery coefficient, static friction, and rolling friction were measured and validated through simulations in EDEM. Optimal values were identified as 0.446, 1.146, and 0.0194, respectively. Full-factorial analysis revealed significant effects on repose angle. Repeated trials confirmed a deviation of only 0.72% from experimental results, validating the calibration method. These findings provide a foundation for improving cotton stalk harvesting and transportation efficiency.

摘要
本研究旨在通过离散元法(DEM)准确标定棉秆与橡胶带在农业机械中的相互作用。通过物理实验，测得关键参数如碰撞恢复系数、静摩擦系数和滚动摩擦系数，并在 EDEM 中进行仿真验证，最佳值分别为 0.446、1.146 和 0.0194。全因子分析显示这些参数对堆积角的影响显著。重复实验结果与实际实验值偏差仅为 0.72%，验证了标定方法的准确性。本研究为优化棉秆收获和运输效率提供了理论基础。

INTRODUCTION
Cotton stalks, a major by-product of cotton production, hold significant value in industries ranging from bioenergy to materials manufacturing. In agricultural machinery, the interaction between cotton stalks and rubber belts is crucial, as these belts play a key role in efficiently pulling and transporting cotton stalks from the field during harvesting operations. However, calibrating key parameters like collision restitution, static friction, and rolling friction remains challenging, often leading to discrepancies between simulations and real-world performance, affecting key metrics such as uprooting efficiency, breakage rate, and missed uprooting rate, thereby causing inefficiencies in machine design.

The previous research on the calibration of cotton stalks has focused primarily on simulating individual mechanical properties or interactions with other materials. For instance, *Zhang et al. (2022)* and *Zhang et al. (2024)* advanced the calibration of cotton stalk parameters using Discrete Element Method (DEM) and response surface methods, improving the accuracy of simulations. Similarly, *Jiang et al. (2023),* expanded on this by incorporating cotton stalk-soil mixtures, enhancing the potential for improving harvesting performance. However, while these studies significantly improve the understanding of cotton stalk simulations, they still fall short of offering practical guidance for optimizing the design of flexible cotton stalk harvesting equipment.

Further contributions have come from studies that addressed the interaction between plant materials and rubber belts, such as *Jin et al. (2022),* who calibrated contact parameters between corn seeds and rubber belts, and *Sun et al. (2019),* who studied the contact parameters between wheat and conveyor belts. These studies helped enrich the field of plant-rubber belt interface research, yet they do not fully address the complexities involved in cotton stalk harvesting machinery design. *Li et al. (2022)* also conducted detailed DEM analyses to improve simulation accuracy in complex systems, but similar to the other studies, this

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research does not provide a complete framework for optimizing the design of rubber belt cotton stalk harvesting equipment. On the other hand, the calibration of rubber materials and their interactions with agricultural materials has received significant attention. *Rossow et al. (2021)* and *Zhao et al. (2023)* examined the interaction between rubber conveyor belts and various materials, contributing valuable insights into friction and wear behaviors. *Nattino et al. (2014)* also refined rubber material calibration through statistical models to improve predictive accuracy. While these studies do not directly address the optimization of rubber belt cotton stalk harvesting equipment, highlighting a clear gap in research.

Most existing studies have concentrated either on the mechanical properties of cotton stalks or on the contact characteristics of rubber with other materials. This study fills that gap by focusing on the dynamic interaction between cotton stalks and rubber belts, providing a more holistic view that directly contributes to the optimization of harvesting equipment.

MATERIALS AND METHODS

Test material

Cotton Stalks: The primary test material was Xinluzao 66 cotton stalks, sourced from Anning Town, Urumqi City (43°58′N, 87°30′E) in Xinjiang, China. The stalks were selected for uniform size and moisture content, crucial for accurate results. They were cut to 25 mm lengths, with key properties like density (1.08 g/cm³) and moisture content standardized using a drying oven at 105°C for 24 hours.

Rubber Belts: A standard EP100-640 × 3(4+2) rubber belt, widely used in agricultural machinery, was chosen for the tests. The belt measures 300 mm × 350 mm × 8 mm and features a polyester (EP) fabric core, providing high tensile strength and durability.

Test method

Contact coefficient calibration experiment: Physical experiments and EDEM 2022 software were used to calibrate the contact coefficient between cotton stalks and rubber belts, including collision recovery coefficient, static friction coefficient, and rolling friction coefficient. Single-factor experiments were employed to optimize each parameter, using average area count, slip angle, and rolling distance as metrics. Lastly, the Angle of Repose was measured using the Cylinder Lifting Method, which evaluated the pile angle of the cotton stalks on the rubber belts.

Full Factorial Experimental Design: A full factorial experimental design was implemented using Design Expert 10.0 to analyze the significance of the cotton stalk-rubber belt contact parameters and their interactions. This provided insight into both individual and combined parameter effects.

Box-Behnken test Design: The parameters were optimized through a Box-Behnken Design (BBD) and response surface analysis. A binary regression equation was derived, targeting the Angle of Repose, and the optimal parameter values were determined based on this analysis.

The coefficient of variation (CV) was 1.01%, indicating good reliability of the test, and the binary regression equation is shown in equation (2):

$$\theta = 43.04 + 0.8A + 0.225B - 1.25C - 0.625AB + 1.775AC \\ +0.375BC - 1.8325A^2 - 2.3325B^2 - 1.7825C^2 \quad (1)$$

By using the Design-Expert software constraint solving tool to find the minimum extreme value of the error point for equation (2), the angle of repose is used as the target to find the best value of parameters, and the collision recovery coefficient (A), static friction coefficient (B), and rolling friction coefficient (C) between cotton stalk and rubber belt are 0.446, 1.146, and 0.0197.

Cotton stalk-rubber belt contact parameter calibration experiment

Using EDEM 2022, contact parameters were simulated to enhance the accuracy of physical tests, focusing on single-factor experiments for optimal parameter isolation. The Hertz-Mindlin no-slip contact model was applied to simulate cotton stalk-rubber belt interactions during the angle of repose test, given the minimal bonding forces between particles *(Hu et al., 2022)*. To replicate the cylindrical shape of cotton stalk shown in Figure 1(a), models were created with a diameter of 10 mm and lengths of 25 mm *(Zhang et al., 2024)*, as shown in Figure 1(b), ensuring accurate calibration of the interaction.

(a) Cotton stalk

(b) Discrete element model

Fig. 1 - Cotton stalk model

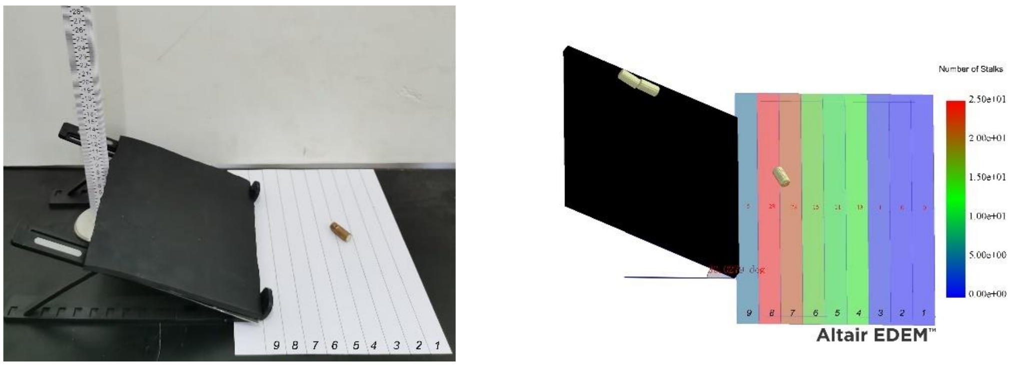
The results from the physical tests, combined with a review of relevant literature, provide the characteristic contact parameters for cotton stalks and rubber belts, as summarized in Table 1. A review of the literature *(Zhang et al., 2024; Jiang et al., 2021)* identified a range of values for the angle of repose, bending, and fracture characteristics, along with other key contact parameters for cotton stalks.

Table 1

Simulation parameters of materials in contact with cotton stalks

Materials	Parameter	Value	Units
Cotton stalk	Poisson's ratio	0.35	-
Cotton stalk	Shear modulus	0.69	GPa
Cotton stalk	Density	1080	kg/m^3
Rubber Belt	Poisson's ratio	0.48	-
Rubber Belt	Shear modulus	1 × 10^9	GPa
Rubber Belt	Density	1.38	kg/m^3
Stalk-Rubber Belt	Collision recovery coefficient	0.35~0.5	-
Stalk-Rubber Belt	Static friction factor	0.5~1.5	-
Stalk-Rubber Belt	Rolling friction factor	0.015~0.025	-

Collision Recovery Coefficient



(a) Experiment of Flatbed method *(b) Simulation of Flatbed method*

Fig. 2 - Measurement of Collision Recovery Coefficient for cotton stalk and rubber belt

To accurately measure the collision recovery coefficient between cotton stalks and a rubber belt using the Flatbed method *(Zhang et al., 2024)*, a simple yet effective apparatus was designed as shown in Figure 2(a). The apparatus featured an inclined rubber belt plate, measuring 180 mm by 200 mm, set at a 30° angle. This setup allowed cotton stalk particles, each 25 mm in length, to be released from a height of 300 mm, enabling free fall onto the plate. Below the plate, a 9-grid paper with 25 mm spaced grids was placed to record the landing positions.

To facilitate the subsequent calculation of the area count, the method from *(Niu et al., 2022)* for measuring the collision recovery coefficient of feed was referenced. Using the average area as the target value and applying the equation as follow:

$$K = \frac{1}{N_{total}} \sum_{k=1}^{n} (kN_k) \tag{1}$$

where:

K - the average number of areas;

N_{total} - the total number of cotton stalk models;

n - the total number of areas;

N_k - the number of models in area k, where k is the area number.

The results of the collision recovery coefficient experiment are shown in Table 2. According to the aforementioned equation (1), the average area count was calculated to be 7.01. By measuring the average area count from particle landing positions, an accurate representation of the stalks' rebound behavior was obtained.

Table 2

Experimental Results of Collision Recovery Coefficient Measurement

Serial number	1	2	3	4	5	6	7	8	9
Number of stalks	0	0	2	2	5	16	37	35	3

To determine the optimal collision recovery coefficient between cotton stalks and the rubber belt in simulations, as shown in Figure 2(b), the coefficient was varied from 0.35 to 0.5, with a step size of 0.03. Six experiments, as shown in Table 3, were conducted to assess how changes in this coefficient affect the spatial dispersion of cotton stalks particles upon contact. The results in Table 3 showed that as the coefficient increased, the mean number of regions decreased, with the optimal value of 0.44 yielding the lowest error rate of 0.7%. This suggests that a coefficient of 0.44 most accurately replicates the interaction for further simulations.

Table 3

Simulation Results of Collision Recovery Coefficient Measurement

Serial number	Collision recovery coefficient	Mean number of regions	Error
1	0.35	7.85	12.0%
2	0.38	7.58	8.1%
3	0.41	7.53	7.4%
4	0.44	7.06	0.7%
5	0.47	6.76	3.6%
6	0.50	6.52	7.0%

Static Friction Coefficient

To measure the static friction coefficient between cotton stalks and the rubber belt, an inclined plane method was used *(Du et al., 2012)*. A rubber belt (300 mm × 350 mm × 8 mm) was fixed onto a board, and a cotton stalk was placed on the belt, as shown in Figure 3(a). The belt was gradually lifted until the stalk began to slide, and the angle (θ) between the belt and the horizontal plane was measured. This process was repeated 10 times, as shown in Table 4, yielding an average θ of 53.7°.

(a) Experiment of Inclined Plane Method *(b) Simulation of Inclined Plane Method*

Fig. 3 - Measurement of Static friction coefficient for cotton stalk and rubber belt

Table 4

Static Friction Measurement of Experimental Cotton Stalk Slip Angle

Serial number	1	2	3	4	5	6	7	8	9	10
1	69°	48°	45°	47°	74°	53°	61°	49°	46°	48°
2	64°	52°	47°	50°	65°	51°	52°	50°	49°	55°
3	44°	55°	46°	69°	54°	70°	44°	59°	49°	47°
Mean	59°	51.6°	46°	55.3°	64.3°	58°	52.3°	52.6°	48°	50°

A simulation experiment was conducted to measure the static friction coefficient between cotton stalks and the rubber belt using the inclined plane sliding test as shown in Figure 3(b). The collision recovery coefficient between the cotton stalks and the rubber belt was set at 0.4, while the dynamic friction coefficient was set to 0.

The static friction coefficient was tested over a range of 0.5 to 1.5, with a step size of 0.1, resulting in a total of 11 simulation experiments. The results of each simulation, along with the corresponding levels of the static friction coefficient, are summarized in the Table 5.

Table 5

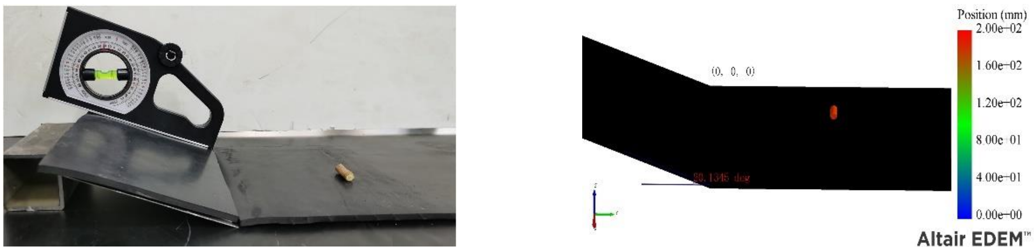
Static Friction Measurement of Cotton Stalk Slip Angle Simulation

Serial no.	Coefficient of static friction	Slipping angle	Error
1	0.5	30.4°	43.4%
2	0.6	34.5°	35.6%
3	0.7	38.8°	27.7%
4	0.8	44.4°	17.3%
5	0.9	47.1°	12.3%
6	1.0	48.3°	10.1%
7	1.1	52.1°	3.0%
8	1.2	53.1°	1.1%
9	1.3	54.5°	1.5%
10	1.4	58.2°	8.4%
11	1.5	61.2°	14.0%

Based on the static friction measurement results shown in Table 5, the slipping angle of cotton stalks increases as the coefficient of static friction increases. The error percentage, however, decreases as the static friction coefficient increases, reaching its lowest point (1.1%) at a coefficient of 1.2. This suggests that a friction coefficient between 1.0 and 1.2 offers the most accurate prediction of the cotton stalk's slip angle in simulations, with minimal error.

The Rolling Friction Coefficient

To assess the rolling friction between cotton stalks and the rubber belt, the Oblique Rolling Method was employed *(Liang et al., 2022)*, two rubber belt sections were mounted onto iron plates with dimensions of 350 mm × 300 mm × 8 mm and 600 mm × 500 mm × 8 mm, as shown in Figure 4(a). Preliminary tests revealed that when the angle of the first belt exceeded 25°, cotton stalks would bounce upon reaching the second belt, disrupting the smooth rolling motion. To prevent this, the belt was inclined at a consistent angle of 20°.



(a) Experiment of Oblique Rolling Method *(b) Simulation of Oblique Rolling Method*

Fig. 4 - Measurement of Rolling Friction Coefficient for cotton stalk and rubber belt

During the main experiment, cotton stalks were released from a height of 100 mm above the second belt to measure the rolling distance on the horizontal section. If a cotton stalk rolled off the belt, the test was repeated to ensure accuracy.

After conducting 10 valid trials, the average rolling distance was found to be 190.5 mm, as shown in Table 6, indicating a smooth interaction between the cotton stalk and the rubber belt at the given conditions.

Table 6

Rolling friction determination of experimental cotton stalk rolling distance

Serial number	1	2	3	4	5	6	7	8	9	10	Mean
Rolling distance (mm)	138	249	218	204	198	181	219	134	153	211	190.5

Figure 4(b) shows the Simulation of Oblique Rolling Method in EDEM, the results of the rolling friction simulation experiment for cotton stalks are summarized in Table 7. In this experiment, the rolling friction coefficient was incrementally varied from 0.015 to 0.025, with a step size of 0.002. The findings demonstrate that as the rolling friction coefficient increases, the rolling distance of the cotton stalks decreases correspondingly. Notably, a coefficient of 0.019 was identified as the optimal value, yielding the smallest error of 1.6%, making it the most accurate for simulating the rolling motion of cotton stalks on the rubber belt. Consequently, this coefficient is recommended as the most suitable parameter for modelling cotton stalk-rubber belt interactions in discrete element simulations.

Table 7

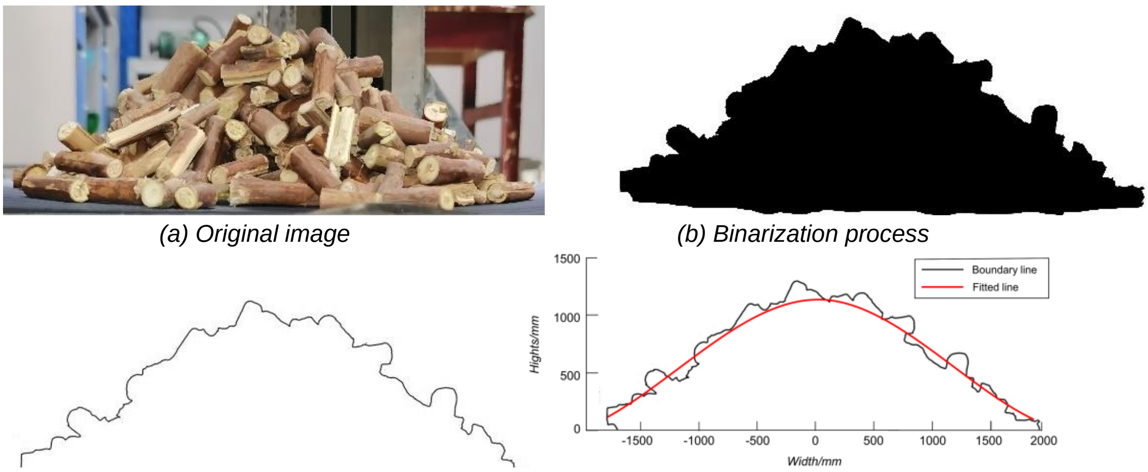
Rolling friction determination of cotton stalk rolling distance simulation

Serial number	Rolling Friction Coefficient	Rolling distance (mm)	Error
1	0.015	212.6	11.6%
2	0.017	210.2	10.3%
3	0.019	193.6	1.6%
4	0.021	186.7	2.0%
5	0.023	163.6	14.1%
6	0.025	155.9	18.2%

Angle of Repose

The angle of repose is a macroscopic parameter that reflects the flow and friction characteristics of granular materials (*Zhang et al., 2022*), directly linked to contact parameters and the material's inherent physical properties. In this study, the angle of repose of cotton stalks on a rubber belt was measured to verify the accuracy of the contact parameters between the stalks and the rubber belt.

For the experiment, cotton stalks with diameters of 10 mm were cut to a uniform length of 25 mm, with 340 particles being used, as shown in Figure 5(a). A cylindrical rubber tube was placed vertically on the rubber belt, and the stalks were released at a uniform speed of 0.03 m/s (*Wang et al., 2022*), allowing them to naturally accumulate on the belt. The image of the cotton stalk's angle of repose was first binarized using MATLAB software to differentiate between the stalks and the background, as shown in Figure 5(b). Photoshop was then employed to extract the edge lines of the binarized image, as shown in Figure 5(c). Finally, the least squares method was applied to fit the boundary curve, as shown in Figure 5(d), In this figure, the x and y axes represent the width and heights of stalks, respectively. The experiment was repeated five times, with an average angle of repose measured at 43.04°.



(a) Original image *(b) Binarization process*

(c) Extraction edge *(d) Fitting the curve*

Fig. 5 - Image processing

In the EDEM simulation experiments, conducted under the same conditions as the physical tests, the Hertz-Mindlin contact model was utilized to simulate the interactions between particles. The particle factory, positioned 100 mm above the simulation base, generated cotton stalk particles at a rate of 114 particles per second, ensuring consistency with the stalk diameter. Figure 6(a) shows the static state of cotton stalk particles after generation, while Figure 6(b) shows the state of cotton stalk particles after the cylinder is lifted and the flow stops.

(a) Static status of cotton stalks *(b) Simulated angle of repose of cotton stalks*

Fig. 6 - Cotton Stalks simulation stacking angle experiment

From these experiments, it was observed that the selected parameters closely replicated the physical behavior of the cotton stalks, providing reliable data for further analysis. Therefore, this setup and parameter configuration proved effective for accurately modeling the mechanical interactions of cotton stalk particles in discrete element simulations.

RESULTS AND ANALYSIS

A full factorial experiment was designed to investigate the factors affecting the angle of repose (*θ*) in the contact parameters between cotton stalks and the rubber belt. The experiment considered three factors: the collision recovery coefficient (A), static friction coefficient (B), and rolling friction coefficient (C), designed in Table 8. Since it was unclear whether each factor had a significant effect on the angle of repose, the experiment aimed to identify significant factors influencing *θ*.

The design also included three central points to ensure accuracy in the analysis. The levels of each factor are detailed in Table 9, with a total of 11 experimental designs established.

Table 8

Experimental factor level design

Experimental factor	-1	0	1
A	0.41	0.44	0.47
B	1.0	1.20	1.40
C	0.017	0.021	0.025

Table 9

Experimental design of contact parameters

Serial number	A	B	C	*Θ (°)*
1	-1	-1	-1	40.9
2	1	-1	-1	41.2
3	-1	1	-1	42.8
4	1	1	-1	38.9
5	-1	-1	1	33.8
6	1	-1	1	40.7
7	-1	1	1	36.5
8	1	1	1	40.5
9	0	0	0	43.6
10	0	0	0	42.8
11	0	0	0	43.3

Table 10

Parameter significance analysis

Parameter	Effect	Sum of square	Mean square	F Value	P-Value	Significance ranking
A	1.825	6.66	6.66	37.15	0.009	3
B	0.525	0.55	0.55	3.07	0.178	6
C	-3.075	18.91	18.91	105.47	0.002	2
AB	-1.775	6.3	6.3	35.14	0.01	4
AC	3.625	26.28	26.28	146.57	0.001	1
BC	0.725	1.05	1.05	5.86	0.094	5

Based on the results shown in Table 10, a significance analysis of the parameters was conducted to evaluate their impact on the angle of repose. The interaction between the rolling friction coefficient and the static friction factor (AC) has the highest significance, as shown by its P-value of 0.001 and F value of 146.57, making it the most influential factor. In addition, the rolling friction coefficient (C) also plays a crucial role, with a P-value of 0.002 and an F value of 105.47, ranking second in significance. This highlights its strong independent effect on the angle of repose. Therefore, the analysis indicates that rolling friction (C) and its interaction with static friction (AC) should be prioritized for tuning in future simulations, as they exhibit the most significant effects on the simulation results, particularly in modeling the behavior of cotton stalks in discrete element simulations.

BBD response surface test results and analysis

To determine the optimal contact parameters between cotton stalks and the rubber belt, the Box-Behnken Design (BBD) was applied *(Coetzee et al., 2017)*. In this study, A three-factor, three-level combination design test was established with 17 test simulations and five sets of tests at the central level in Table 11, and the BBD response surface test analysis of variance is shown in Table 12.

Table 11

BBD Response surface design

Serial number	A	B	C	*θ*(°)
1	-1	-1	0	37.4
2	1	-1	0	40.0
3	-1	1	0	39.0
4	1	1	0	39.1
5	-1	0	-1	41.8
6	1	0	-1	40.1
7	-1	0	1	35.2
8	1	0	1	40.6
9	0	-1	-1	40.0
10	0	1	-1	39.8
11	0	-1	1	37.3
12	0	1	1	38.6
13	0	0	0	42.6
14	0	0	0	43.2
15	0	0	0	43.3
16	0	0	0	42.8
17	0	0	0	43.3

Table 12

BBD Response surface analysis of variance

Source	Freedom Degrees	Mean Square	F Value	P-Value Prob
Model	9	9.89	59.56	<0.0001
A	1	5.12	30.84	0.0009
B	1	0.41	2.44	0.1623

Source	Freedom Degrees	Mean Square	F Value	P-Value Prob
C	1	12.5	75.3	<0.0001
AB	1	1.56	9.41	0.0181
AC	1	12.6	75.92	<0.0001
BC	1	0.56	3.39	0.1082
A^2	1	14.14	85.18	<0.0001
B^2	1	22.91	138	<0.0001
C^2	1	13.38	80.59	<0.0001
Residual	7	0.17	-	-
Lack of Fit	3	0.25	2.43	0.257
Pure Error	4	0.1	-	-
Cor Total	13	-	-	-

Analysis of the response surface test variance data revealed that factors (B) and (BC) had no significant effect on the angle of repose. The regression model yielded a coefficient of determination R^2 of 0.9871, indicating a high level of model fit. Additionally, the lack-of-fit P-value was greater than 0.05, confirming that the model was statistically significant and the lack of fit was not significant.

Compared with other studies, this research advances calibration efforts beyond the traditional focus on isolated parameters, such as the mechanical properties of cotton stalks or individual interactions between rubber belts and materials, as seen in *Zhang et al. (2024)*, which improved the accuracy of simulations for chopped cotton stalks. Building on that foundation, this study incorporates a more comprehensive set of parameters, including the coefficients of collision recovery, static friction, and rolling friction. These parameters are further validated through real-world experimental data, enhancing the accuracy and realism of the simulation models. Regarding device design optimization, this study differs from works like those by *Zhang et al. (2023)* and *Li et al. (2022)*, which primarily concentrated on simulation accuracy and material-specific calibration.

This study provides a more refined, practical approach to simulating cotton stalk-rubber belt interactions, addressing a gap in the current literature by providing valuable insights for the optimization of flexible cotton stalk harvesting equipment. The innovation of this research lies in its practical application for optimizing the design of harvesting equipment.

CONCLUSIONS

(1) Through physical experiments, such as the flatbed method and the inclined plane method, the contact parameters between cotton stalks and rubber belts were calibrated. The flatbed method measured the average area count was calculated to be 7.01, while the inclined plane method yielded an average sliding angle of 53.7° and an average rolling distance of 190.5 mm for the cotton stalks. Using the average area count, sliding angle, and rolling distance as evaluation indicators, simulations of single-factor experiments based on EDEM 2022 software determined the optimal contact parameters between cotton stalks and rubber belts: a collision recovery coefficient of 0.44, a static friction coefficient of 1.2, and a rolling friction coefficient of 0.019.

(2) The full-factorial experimental analysis revealed that both the collision recovery coefficient and the rolling friction coefficient significantly affected the repose angle. Furthermore, the interaction between the collision recovery coefficient and the static friction coefficient, as well as between the collision recovery coefficient and the rolling friction coefficient, had a considerable impact on the repose angle.

(3) Using Design Expert 10.0 software, the response surface analysis, contour plots, and regression equations identified the optimal cotton stalk-rubber belt contact parameters: a collision recovery coefficient of 0.446, a static friction coefficient of 1.146, and a rolling friction coefficient of 0.0194. Repeated experiments (n=5) resulted in an average repose angle of 42.73°, with a deviation of 0.72% from the actual experimental results.

ACKNOWLEDGEMENT

This study was supported by the Xinjiang Uygur Autonomous Region Youth Science Fund (Grant No.2022D01B91) and the National Nature Foundation Project (Grant No. 52365038).

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