# VIBRATION PARAMETER CALIBRATION AND TEST OF TIGER NUT BASED ON DISCRETE ELEMENT METHOD

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# 基于离散元法的油莎豆振动参数标定与试验

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## ABSTRACT

*In this study, the parameters of tiger nut were calibrated based on discrete element method, and significant influencing factors and optimal levels were selected by Plackett-Burman test, steepest climb test and center compound test, and verified by electromagnetic vibration hopper bench test. The results show that the relative error between the simulated resting angle and the actual resting angle is only 0.381%. The fitting degree of the model is 96.32% and 94.57% respectively, which can provide theoretical basis for the study of the parameters and discrete element simulation of tiger nut.*

## 摘要

*本研究基于离散元法对油莎豆参数进行标定，采用 Plackett-Burman 试验、最陡爬坡试验和中心复合试验筛选出显著影响因素及最优水平，进行电磁振动料斗台架试验进行验证。结果表明：仿真休止角与实际休止角相对误差仅为 0.381%；电磁振动料斗输送时间的预测模型拟合度为 96.32%，质量流率拟合度为 94.57%，可为油莎豆参数特性研究以及离散元仿真工作提供理论依据。*

## INTRODUCTION

Tiger nut is known as “underground walnut”. It has high oil yield and its yield ranks first among oil crops (*Rebezov et al., 2023; Udefa et al., 2020; Sobhy et al., 2015*). It is a new economic crop with high comprehensive utilization value (*Wang et al., 2022; Guo et al., 2021; Umukoro et al., 2020; Pascual et al., 2000*). Automatic feeding is an important part of Tiger nut seed selection and processing, and conveying stability is an important evaluation index of feeding quality. At present, electromagnetic vibration hoppers are mostly used in China to transport peanuts, corn and other materials in an orderly manner. However, problems such as backward slip and in-situ beating during the transportation of Tiger nut are prominent, which seriously affect the efficiency of Tiger nut seed selection. At the same time, there are few studies on the basic theory of Tiger nut, and it is impossible to determine the motion law of Tiger nut under high frequency vibration, and the transportation accuracy is not high in actual operation (*Xing et al., 2017; Singh et al., 2020; Mišljen et al., 2016*). Therefore, it is of great significance to study the basic physical parameters of Tiger nut for realizing the accurate and stable feeding of Tiger nut and promoting the development of Tiger nut industrial chain.

In the process of automatic feeding, the trajectory of Tiger nut is complex and changeable under the action of high frequency vibration of electromagnetic vibration hopper. EDEM software is often used for discrete element simulation to explore the movement law of agricultural granular materials and the best operating parameters of the machine. At present, most of the researches on the calibration of material parameters only verify the accuracy of the calibration parameters through the angle of repose test, which is different from the actual working conditions of the material, resulting in the simulation conclusion cannot guide the actual production well (*Hao et al., 2019; Wang et al., 2020; Wu et al., 2020; Shi et al., 2022*). The research objects are mostly peanut seeds, potatoes, wheat grains and other materials. There are few studies on the calibration of the parameter characteristics of the simulation model of Tiger nut tubers.

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In this paper, the intrinsic parameters and contact parameters of Tiger nut tubers were determined by physical experiments. The simulation model was established in EDEM software to simulate the accumulation state of Tiger nut. Taking the angle of repose of Tiger nut as the response value, the Plackett-Burman test was used to screen out the significant influencing factors, and the central composite test of response surface method was used to obtain the optimal level. Through the bench test of electromagnetic vibration hopper, the motion state of Tiger nut was reflected and verified by conveying time and mass flow rate. This paper can provide a theoretical reference for the application of discrete element method to the study of small seed parameter characteristics and the study of motion state under high frequency vibration.

## MATERIALS AND METHODS

### *Determination of intrinsic parameters of Tiger nut tubers*

A total of 1000 grains were randomly selected from the Tiger nut samples and placed in a combined sieve for manual screening and separation. 100 grains were randomly selected, and the three-axis size was measured using a vernier caliper. The results are shown in Table 1.

**Table 1**

**Triaxial dimension of the Tiger nut tubers**

| Triaxial Dimension | Small Tuber | Medium Tuber | Large Tuber |
|---|---|---|---|
| Length *L*/mm | 12.05±0.77 | 13.34±0.93 | 14.78±1.06 |
| Width *W*/mm | 10.31±0.64 | 13.14±0.85 | 14.45±1.02 |
| Height *H*/mm | 9.83±0.59 | 13.36±0.87 | 12.93±0.81 |

The average moisture content of Tiger nut was 48.90% according to the wet basis representation method.

The cylindrical sample compression test of randomly selected Tiger nut was carried out by microcomputer controlled electronic universal testing machine, and the average Poisson's ratio of Tiger nut was 0.478.

### *Determination of elastic modulus and shear modulus*

The Tiger nut was randomly selected and the original height was measured. Then it was fixed on the test machine platform and pressurized along the height direction of Tiger nut at a loading speed of 0.1 mm/s (*Hao et al., 2021*). The software post-processing module was used to read the real-time data of load and deformation, and 100 tests were repeated. The shear modulus of Tiger nut tubers ranged from 105 MPa~127 MPa, with an average of 116.82 MPa.

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\lim\limits_{T\to 0}\left(\frac{\Delta T}{T}\right)} \tag{1}$$

where:

E is the elastic modulus of Tiger nut, [MPa]; σ is the maximum compressive stress, [MPa]; ε is strain; F is the axial load, [N]; A is the contact area, [mm2]; ∆T is the high deformation of Tiger nut, [mm]; G is the shear modulus of Tiger nut, [MPa];

### *Determination of friction coefficient between Tiger nut tuber and steel plate*

In this experiment, the static friction coefficient between Tiger nut tubers and steel plates was measured by a self-made friction coefficient measuring device. The test device is shown in Fig.1.

Four Tiger nut tubers (*Wu et al., 2020*) were bonded using glue and placed flat on a horizontal steel plate. The sliding friction angle was determined by measuring the inclination angle at which the tuber started sliding downwards on the slope. The static friction coefficient between the Tiger nut tuber and the steel plate was calculated based on 50 repeated tests, ranging from 0.15 to 0.35, averaging 0.26. The rolling friction coefficient was also measured using the same method, resulting in a range of 0.017 to 0.035, with an average value of 0.027.

### *Determination of friction coefficient between Tiger nut tubers*

The Tiger nut tubers were closely arranged according to the shape. The bottom of some large-sized Tiger nut tubers was removed and adhered to the plane test plate, as shown in Fig. 2 (*Wu et al., 2020*). The above tests were repeated as a whole as a material to be tested, and the static friction coefficient between the tubers of Tiger nut ranged from 0.26~0.44, with an average value of 0.34. The rolling friction coefficient between Tiger nut tubers ranged from 0.027~0.045, with an average of 0.035.


**Fig. 1 – Static friction coefficient measurement**

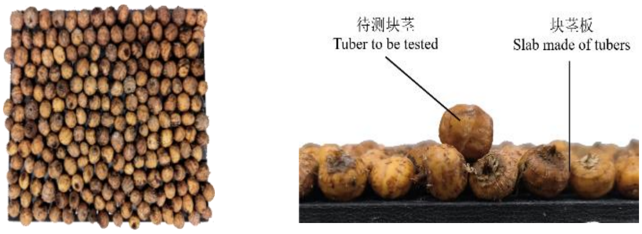



**Fig. 2 – Measurement of friction coefficient between tubers**

***Collision restitution coefficient test***

The high-speed camera was used to collect and process the image of tuber falling motion, and the recovery coefficient of Tiger nut was determined (*Liu et al., 2018*). The materials to be tested are steel plate and Tiger nut tuber plate. The test height is 200 mm, and the vertical height between the chute of electromagnetic vibration hopper and the material box is set.

The material to be inspected is attached to the slope instrument, and the slope angle is 30°. The Tiger nut tubers were fixed on a tripod, and the vertical height from the material to be inspected was 200 mm. After the free fall of the tuber, the complete motion process is collected by a high-speed camera, and the trajectory image is generated as shown in Fig. 3.

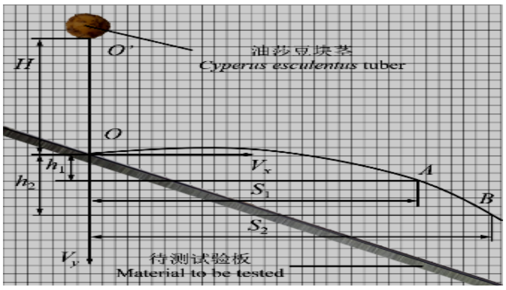



**Fig. 3 – Principle of crash recovery coefficient determination test**

*O' is the original position; O is the origin; H is the OO' distance, [mm]; A and B are the observation points; $h_1$ and $h_2$ are the height displacements, [mm]; $S_1$ and $S_2$ are the horizontal displacements, [mm]; $V_x$ and $V_y$ are the horizontal and vertical fractional velocities, [$m \cdot s^{-1}$];*

The calculation formula of the recovery coefficient of Tiger nut is as follows:

$$e = \left|\frac{V_n}{V_n'}\right| = \left|\frac{\sqrt{V_x^2}\,\cos[60^{\circ} + \arctan C\,\tan(V_y/V_x)]}{V_0 \cos 30^{\circ}}\right| \tag{2}$$

where:

$e$ is the collision recovery coefficient of Tiger nut tuber-tested material; $v_1$ is the instantaneous separation velocity in the normal direction of the collision point between the Tiger nut tuber and the material to be tested, [m/s]; $v_0$ is the instantaneous contact velocity of the collision between the Tiger nut tuber and the material to be tested, [m/s]; $H_1$ is the maximum height of collision rebound between Tiger nut tubers and materials to be tested, [mm]; $H_0$ is the falling height of Tiger nut tuber, [mm];

Repeated 50 tests, the range of collision recovery coefficient between Tiger nut tubers was 0.28~0.45, and the average value was 0.36. The collision recovery coefficient of Tiger nut tuber-steel plate ranged from 0.60~0.76, with an average of 0.70.

***Angle of repose determination test***

The actual accumulation test of Tiger nut was carried out by using the device shown in Fig. 4 (*Jia et al., 2021*).


**Fig. 4 – Physical Repose angle test of Tiger nut tubers**

According to the pre-test, the lifting speed of the cylinder was set to be 0.1 m/s, and the tuber fell under the action of gravity. After the oil sands pile was stabilized, the lifting was stopped, and then the positive and negative sides of the oil sands pile were photographed horizontally with the steel plate platform (*Han et al., 2019; Pan et al., 2020*).

a. Original image b. Binarization c. Edge detection d. Edge contour

**Fig. 5 – Edge contour extraction and fitting process of stacking angle**

Image processing was performed using MATLAB to remove the internal interference contour of the Tiger nut, and only the outer contour was retained, as shown in Fig. 5. The software Origin was imported to linearly fit the outer contour of the Tiger nut, as shown in Fig. 6 (*Pue et al., 2019; Tekeste et al., 2018; Coetzee et al., 2016*). The angle of repose of the actual stacking test of Tiger nut tubers was 30.70 ° by repeating the test for 100 times and taking the average value.

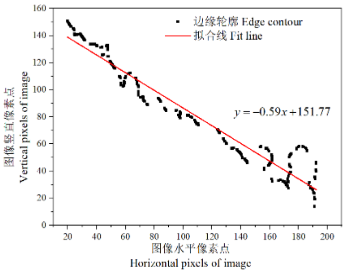



**Fig. 6 – Boundary fitting of one-side stacking angle**

**Fig. 7 – Discrete element model of Tiger nut tubers**

***Tiger nut tuber model and Tiger nut tuber contact mechanic model***

The three-dimensional dimensions and shape characteristics of tuber were determined by using a three-dimensional laser scanner. By scanning to reconstruct its morphological features, the software automatically fills in three discrete element models of the model, as shown in Fig. 7. The Hertz-Mindlin (no slip) contact model was selected for simulation. The Hertz-Mindlin (no slip) contact model was selected for simulation.

***Plackett-Burman Design experiment***

Between the references and the experiments in this paper, the range of each parameter is determined as shown in Table 2, and the experimental design table and results are shown in Table 3. The significance analysis of Plackett-Buman test parameters is shown in Table 4. Regression model equation represented by the coding factor is:

$$\eta = 29.91 - 0.17A + 0.17B + 0.29C + 0.49D + 1.40E + 2.28F - 0.14G - 0.43H + 0.50J \quad (3)$$

**Table 2**

**Factors and levels table of Plackett-Burman Design**

| Symbol | Parameter | Level | |
|---|---|---|---|
| | | -1 | +1 |
| A | Tiger nut Poisson 's ratio | 0.464 | 0.486 |
| B | Density of Tiger nut /(kg·m$^{-3}$) | 2700 | 3000 |
| C | Shear modulus of Tiger nut /MPa | 105 | 127 |
| D | Recovery coefficient between tubers of Tiger nut | 0.28 | 0.45 |
| E | Static friction coefficient between Tiger nut tubers | 0.26 | 0.44 |
| F | Rolling friction coefficient between Tiger nut tubers | 0.027 | 0.045 |
| G | Tiger nut-steel plate recovery coefficient | 0.60 | 0.76 |
| H | Tiger nut-steel plate static friction coefficient | 0.15 | 0.35 |
| J | Tiger nut-steel plate rolling friction coefficient | 0.017 | 0.035 |
| K | virtual parameter | —— | —— |

Table 3

**Design and results of Plackett-Burman test scheme**

| No. | A | B | C | D | E | F | G | H | I | J | K | Repose angle η/(°) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | 34.039 |
| 2 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 26.418 |
| 3 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | 26.424 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 29.741 |
| 5 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 31.06 |
| 6 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | 25.776 |
| 7 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | 30.372 |
| 8 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 26.065 |
| 9 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 33.441 |
| 10 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 33.189 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 29.46 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 29.84 |
| 13 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 30.729 |
| 14 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | 30.978 |
| 15 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 31.06 |

The overall model $P < 0.01$, indicating a significant difference, the determination coefficient $R_2 = 0.9973$, indicating that the regression model is suitable for 99.73% of the test data. After ignoring the non-significant factors, comparing the F values, the order of the influence of each factor on the test angle of repose is F > E > J > D > H > C.

***Design of steepest ascent experiment***

In summary, the static friction coefficient (E) and rolling friction coefficient (F) between Tiger nut tubers were selected as the test factors, and the value range was further determined by the steepest climbing test. By increasing E and F from low level to high level with equal step length, the relative error δ between the angle of repose of simulation test η and the angle of repose of actual test $\theta$ can be calculated according to formula (4). The test scheme and results are shown in table 5.

The significant influencing factors of the simulated angle of repose are selected as the test factors, and the range of values is reduced by the steepest climbing test. The relative error δ between the simulated angle of repose η and the actual angle of repose $\theta$ is:

$$\delta = \frac{|\eta-\theta|}{\theta} \times 100\% \tag{4}$$

Table 4

**Plackett - Burman design regression model analysis of variance of characteristic parameters**

| Source | Standardization effect | Sum of squares | Contribution rate/% | F value | p value |
|---|---|---|---|---|---|
| Model | —— | 95.62 | —— | 102.56 | 0.0014** |
| A | -0.33 | 0.34 | 0.33 | 3.74 | 0.1487 |
| B | 0.33 | 0.33 | 0.33 | 3.71 | 0.1495 |
| C | 0.59 | 1.04 | 1.03 | 11.60 | 0.0423* |
| D | 0.97 | 2.83 | 2.79 | 31.52 | 0.0112* |
| E | 2.80 | 23.47 | 23.19 | 261.79 | < 0.001*** |
| F | 4.55 | 62.20 | 61.46 | 693.93 | < 0.001*** |
| G | -0.28 | 0.24 | 0.23 | 2.65 | 0.2023 |
| H | -0.86 | 2.23 | 2.20 | 24.84 | 0.0155* |
| J | 0.99 | 2.94 | 2.91 | 32.81 | 0.0106* |

The static friction coefficient (E) between Tiger nut tubers was determined to be 0.305 at low level and 0.395 at high level. The rolling friction coefficient (F) between Tiger nut tubers was 0.0315 at low level and 0.0405 at high level, which was optimized by Central Composite test.

**Table 5**

**Design and results of path of steepest ascent method**

| NO. | E | F | Repose angle η/° | Relative error δ/% |
|---|---|---|---|---|
| 1 | 0.26 | 0.027 | 28.912 | 5.825 |
| 2 | 0.305 | 0.0315 | 29.911 | 2.571 |
| 3 | 0.35 | 0.036 | 31.282 | 1.896 |
| 4 | 0.395 | 0.0405 | 32.039 | 4.362 |
| 5 | 0.44 | 0.045 | 32.984 | 7.439 |

***Central Composite test***

In order to obtain the optimal parameter combination and explore the significance of the influence of the static friction coefficient (E) and the rolling friction coefficient (F) between the tubers of Tiger nut on the simulated angle of repose, the Central Composite test was carried out by Design-Expert V10.0.1. In the data pre-processing interface, five central points were set up, and a total of 13 groups of angle repose tests were carried out. The test results are shown in table 6.

The regression equation of static friction coefficient (E) and rolling friction coefficient (F) between Tiger nut tubers can be obtained by regression fitting of the test results:

$$\eta = 30.38 + 1.11E + 0.46F - 0.27EF - 0.43E^2 - 0.37F^2 \tag{5}$$

**Table 6**

**Scheme and results of Central Composite Design**

| NO. | E | F | Repose angle η/° | Relative error δ/% |
|---|---|---|---|---|
| 1 | -1 | -1 | 27.725 | -9.6905 |
| 2 | 0 | -1.41421 | 29.164 | -5.0033 |
| 3 | 1.41421 | 0 | 31.683 | 3.2020 |
| 4 | 0 | 0 | 30.561 | 0.4528 |
| 5 | 0 | 1.41421 | 30.746 | 0.1498 |
| 6 | 0 | 0 | 30.132 | 1.8501 |
| 7 | 0 | 0 | 31.035 | 1.0912 |
| 8 | 0 | 0 | 30.235 | 1.5147 |
| 9 | 1 | 1 | 30.256 | 1.4463 |
| 10 | -1 | 1 | 28.963 | 5.6580 |
| 11 | -1.41421 | 0 | 27.984 | 8.8469 |
| 12 | 0 | 0 | 29.954 | 2.4300 |
| 13 | 1 | -1 | 30.091 | 1.9837 |

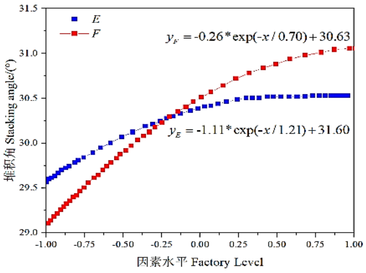
**Table 7**

**Analysis of variance of Central Composite Design regression model**

| Source | Sum of squares | Degree of freedom | Mean square | *F* value | *p* value |
|---|---|---|---|---|---|
| Model | 13.84 | 5 | 2.77 | 10.04 | 0.0043** |
| E | 9.88 | 1 | 9.88 | 35.84 | < 0.001*** |
| F | 1.66 | 1 | 1.66 | 6.01 | 0.0440* |
| EF | 0.29 | 1 | 0.29 | 1.04 | 0.3408 |
| $E^2$ | 1.31 | 1 | 1.31 | 4.75 | 0.0657 |
| $F^2$ | 0.97 | 1 | 0.97 | 3.51 | 0.1030 |
| Residual error | 1.93 | 7 | 0.28 | —— | —— |
| Misfit term | 1.20 | 3 | 0.40 | 2.21 | 0.2292 |
| Pure error | 0.73 | 4 | 0.18 | —— | —— |

Through the analysis of variance of the Central Composite Design regression model, the coefficient of variation C.V. is 1.76%. The smaller the coefficient of variation C.V. is, the more reliable the test data is, and the test results are highly reliable. Ignoring the non-significant factors, comparing the F values, the order of the influence of each factor on the angle of repose of the test is E>F.

Fig. 8 shows the influence of the interaction between the static friction coefficient and the rolling friction coefficient on the simulated angle of repose. When the F level is less than 0.25, the η value increases slowly, but with the increase of E, it increases rapidly and then gradually slows down. When the F level is greater than 0.25, the η value does not change significantly, but increases slowly with the increase of E.



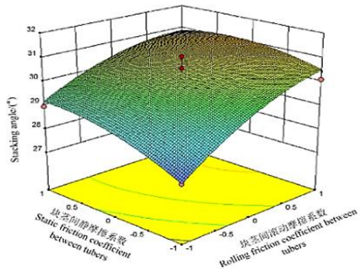
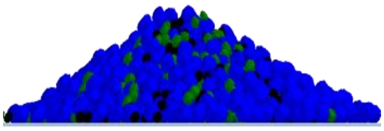



**Fig. 8 – Effect of Repose angle of Tiger nut tuber**

### *Angle of repose verification test*

In the Design-Expert optimization interface, the actual angle of repose of Tiger nut was optimized. The simulation test was carried out under the parameter conditions of the optimized solution to find the most similar parameter conditions to the actual angle of repose, that is, the static friction coefficient between Tiger nut tubers was 0.35 and the rolling friction coefficient was 0.036. Under the optimal parameter conditions, the simulation test is repeated for 10 times to take the average value, and the simulated angle of repose is 30.583°, and the error with the actual angle of repose is only 0.381%. The Tiger nut stacking test is shown in Fig. 9. The trend of the unilateral contour curve of the Tiger nut heap is similar, and the results show that the calibrated Tiger nut parameters are in line with reality.

a. Physical test



b. Simulation test

**Fig. 9 – Comparison between physical and simulation experiment of Repose angle of Tiger nut tuber**

### *Electromagnetic vibration hopper verification test*

When the electromagnetic vibrating hopper works, the hopper performs a composite movement under the action of the electromagnetic vibrator, as shown in Fig. 10. So that the heaps of Tiger nut tubers are dispersed, and then the spiral track rises slowly, thereby achieving orderly transportation (*SINGH et al., 2020; Nguyen et al., 2018*). In the bench test, a total of 1000 small, medium and large Tiger nut tubers with a ratio of 12: 9: 5 were selected according to the proportion of collected samples. The diameter of the hopper was 300 mm and the height was 120 mm. When Tiger nut tubers began to slide evenly from the spiral track, the quality of Tiger nut tubers was recorded every minute, and the mass flow rate was calculated. The test was repeated 20 times under the same voltage condition, and the average value was taken.


**Fig. 10 – Electromagnetic vibration hopper test**

### *Simulated test*

In the simulation experiment, the STL files of Tiger nut tubers and hopper models were imported into EDEM. The number ratio of small, medium and large Tiger nut tubers was 12: 9: 5, the diameter of the hopper was 300 mm, and the height was 120 mm, which was consistent with the actual test.

The compound motion of the hopper is simulated by adding ‘Sinusoidal Translation Kinematic’ and ‘Sinusoidal Rotationnematic Kinematic’ sinusoidal motion functions in the vertical and horizontal circumferential directions. The amplitude is nonlinearly proportional to the voltage. The effective voltage range is selected to be 190~250 V by pre-test. In the simulation, the operating voltage of the electromagnetic vibrator is changed by adjusting and $Z_0$.

**Table 8**

**Relationship between working voltage and amplitude**

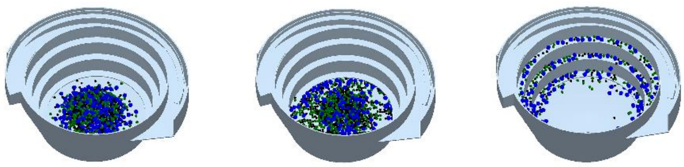
| Voltage $U$/V | Vertical amplitude $Z_0$/mm | Angular amplitude $\theta_0$/(°) |
|---|---|---|
| 190 | 0.334 | 0.534 |
| 200 | 0.349 | 0.571 |
| 210 | 0.360 | 0.603 |
| 220 | 0.365 | 0.629 |
| 230 | 0.377 | 0.665 |
| 240 | 0.391 | 0.692 |
| 250 | 0.402 | 0.727 |

## RESULTS

### *Analysis of test results*

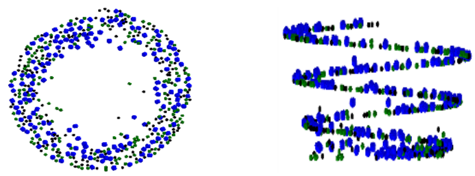
The three motion states of the heaps of Tiger nut tubers in the electromagnetic vibration hopper are shown in Fig. 11. After the simulation test, in order to facilitate observation, the three kinds of Tiger nut tubers were dyed black, the green and blue respectively in the post-processing interface, and the “Grid Bin Group” module was added to the spiral track chute to read the quality of the fallen Tiger nut tubers over time and calculate the mass flow rate. At the same time, the total time T required for each test to complete the transportation is recorded.

In addition, the top view and front view of the movement trajectory of Tiger nut tubers during sorting transportation are shown in Fig. 12. Taking the simulation test of voltage U=220 V (vertical amplitude $Z_0$=0.365, angular amplitude $\theta_0$=0.629) as an example, under the action of vibration, the heaps of Tiger nut tubers first gradually spread from the bottom of the hopper to the surroundings, and then transported upwards along the spiral track, and finally fell from the chute to complete the transportation.



a. Before dispersion b. After dispersion c. Arraying transport

**Fig. 11 – Three movement states of Tiger nut tubers**



a. Top view b. Front view

**Fig. 12 – Sorting conveying motion trajectory**

In the actual test and simulation test, the transmission time curve under different operating voltages is shown in Fig. 13, the change trend of the two curves is basically the same, and the fitting degree of the prediction model is 96.32%. In the simulation experiment, when the working voltage U is lower than 220 V, the movement rate of Tiger nut tubers increases obviously with the increase of working voltage U, when the working voltage U is higher than 220 V, some Tiger nut tubers appear in situ beating on the spiral track or even fall back to the bottom of the hopper. This phenomenon is consistent with the actual test, indicating that the Tiger nut tuber model is reliable and realistic.

As shown in Fig. 14, the change trend of the two curves is basically the same, and the fitting degree of the prediction model is 94.57%. When the operating voltage is in the range of 190~230 V, the mass flow rate increases obviously, and when the operating voltage is in the range of 230~250 V, the mass flow rate tends to be stable.

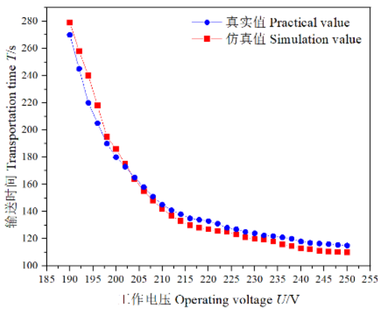



Fig. 13 – Measured results of total transportation time

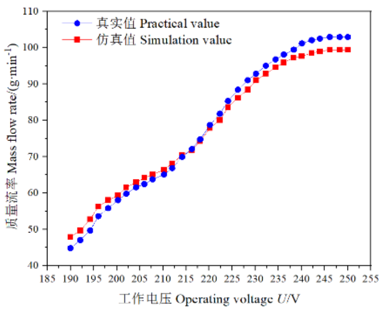



Fig. 14 – Measured results of mass flow rate

By comparing conveying time and mass flow rate at different voltages, it is found that as voltage increases, the actual measured conveying time initially exceeds the simulated value, then becomes smaller and tends to stabilize. The actual measured mass flow rate, on the other hand, starts lower than the simulated value, then increases and tends to stabilize. This inverse relationship between conveying time and mass flow rate results in a curve that accurately represents the actual situation. Overall, the simulation results align well with the actual test results, providing a reliable reflection of real-world operation.

## CONCLUSIONS

(1) The results showed that the static friction coefficient and rolling friction coefficient between Tiger nut tubers had a very significant positive effect on the angle of repose of the simulation test. Other contact parameters have no significant effect on the simulated angle of repose.

(2) The central composite test yielded a reliable quadratic regression model using static friction coefficient and rolling friction coefficient as variables, which were identified as significant influencing factors. To optimize the angle of repose for Tiger nut tubers, numerical optimization was employed. The optimal combination of static friction coefficient and rolling friction coefficient was determined to be 0.35 and 0.036, respectively. The simulated angle of repose for Tiger nut tubers was 30.583°, with a negligible error of only 0.381% compared to the actual test results.

(3) The electromagnetic vibration hopper verification test results demonstrated a close resemblance between the motion state of the actual test and the simulation test of Tiger nut tubers across various working voltages. The prediction model for transportation time exhibited a high fitting degree of 96.32%, while the fitting degree for mass flow rate was 94.57%. These calibration results for the intrinsic parameters and contact parameters of Tiger nut are reliable and accurately reflect the actual test outcomes. They serve as a valuable reference for studying Tiger nut parameters, as well as providing a theoretical basis for discrete element simulation of Tiger nut and optimization of electromagnetic vibration hopper parameters.

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