A STUDY ON THE INFLUENCING FACTORS OF CORN KERNEL COLLISION RESTITUTION COEFFICIENT BASED ON THE OBLIQUE IMPACT COLLISION THEORY

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基于斜撞击碰撞理论的玉米籽粒碰撞恢复系数影响因素研究

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ABSTRACT

Corn kernels collide with the pipe wall during pneumatic conveying, which affects their quality. Based on the theory of oblique impact collision dynamics, this paper investigates the breakage of corn kernels at impact angles ranging from 10°~40° and impact velocities ranging from 6 ~ 28m/s. The results show that secondary collisions have a significant effect on the normal restitution coefficient. As the impact angle increases, all three restitution coefficients tend to increase. At impact angles of 40° and above, the normal and overall restitution coefficients are related to the initial velocity, while the tangential restitution coefficient is not. At impact angles of 30° and above, the normal restitution coefficient is smaller at the top and larger in the middle, and the tangential and overall restitution coefficients are independent of the collision location. The three restitution coefficients when the rotation direction is in the same plane are all smaller than those when rotation occurs perpendicular to the translational plane, with the normal restitution coefficient being most affected by the direction. When the impact angle is between 30°~40°, the tangential restitution coefficient of corn kernels increases with increasing rotational speed. When the impact angle is between 20°~40°, the normal restitution coefficient decreases with increasing rotational speed. When the impact angle is between 10°~40°, the overall restitution coefficient is independent of the rotational speed.

摘要

玉米籽粒在气力输送中会与管壁碰撞进而影响自身质量，本文基于斜撞击碰撞动力学理论，研究了 10°~40°撞击角度下玉米籽粒的破碎情况。结果表明：二次碰撞对法向恢复系数影响较大；随着碰撞角度增加，三种恢复系数均呈增大趋势；40°及以上时，法向及整体恢复系数与初速度相关，切向恢复系数与其无关；30°及以上时，法向恢复系数顶部小、腹部大，切向及整体恢复系数与碰撞部位无关；旋转方向在同一平面内的三个恢复系数均小于在垂直于平动面内发生旋转时的恢复系数，其中法向恢复系数受方向影响最大；30°~40°时，玉米籽粒切向恢复系数随转速增大而增大，20°~40°时，法向恢复系数随转速增大而减小，10°~40°时，整体恢复系数与转速无关。

INTRODUCTION

Particle collisions are widespread in the field of agricultural engineering and hold universal significance. The restitution coefficient, a crucial physical parameter, reflects the ability of particles to recover from deformation and the extent of energy loss.

Currently, dilute-phase pneumatic conveying is widely used for agricultural products, but it has problems such as impact damage to corn kernels (*Zhao et al., 2017*), and high breakage rates (*Wang et al., 2018*). Since grains generally have irregular shapes, the forces they experience during pneumatic conveying are uneven and change randomly, making collisions and breakage behaviors complex (*Yang et al., 2025*). Among various grains, corn is particularly susceptible to damage from collision-induced breakage (*Wang et al., 2024*). Therefore, this study focuses specifically on corn kernels.

During the pneumatic conveying phase, collisions between corn kernels and the pipe wall are inevitable. Extensive research has been conducted on the mechanical characteristics of the collision process. Li designed a drop impact test and found that the ability of corn kernels to withstand impact forces varies significantly depending on the impact location (*Li et al., 2009*). Zhao used discrete element simulation software to create an ellipsoidal rice kernel model to study the mechanical characteristics of the collision process (*Zhao et al., 2013*).

Ozturk experimentally analyzed the restitution coefficients of chickpea and pea seeds (*Ozturk et al., 2010*). Wang experimentally investigated the restitution coefficients of different shaped corn kernels at speeds of 2-4 m/s and impact angles of 30-90° (*Wang et al., 2015*). Chen used the free-fall method and inclined plane method, combined with discrete element simulation and benchmark analysis, to measure the restitution coefficients of spherical soybeans (*Chen et al., 2024*). Wang determined the restitution coefficients of wheat kernels under different influencing factors in a two-dimensional plane based on the principle of kinematic equations (*Wang et al., 2012*). Liu used a high-speed camera to measure and analyze the effects of different influencing factors on the restitution coefficients of sunflower seeds (*Liu et al., 2020*). Current studies on the restitution coefficients of materials mainly focus on experimental and simulation research without considering rotation and low-angle collisions. By approximating the research objects as spherical or ellipsoidal shapes and studying central collisions, the normal restitution coefficient is obtained by examining the ratio of the normal approach velocity to the separation velocity of the kernels before and after the collision (*Feng et al., 2017*). However, for pneumatic conveying, the normal restitution coefficient alone cannot fully describe the state before and after the collision when the impact angle is small (*Wang et al., 2015*). Especially for non-spherical particles like corn kernels, the rebound during low-angle collisions is highly random and accompanied by rotation. Therefore, using only the normal restitution coefficient to represent the state before and after the collision is inaccurate. The tangential restitution coefficient and the effect of rotation should be considered comprehensively.

Previous finite element studies on grains have often made extensive simplifications. However, the geometric characteristics of grains are important parameters, and excessive simplification can affect the accuracy of the solution. Therefore, this paper selects corn kernels with a constant moisture content as the research object. Based on a pneumatic high-speed collision testing platform for agricultural products, and combining the theory of oblique impact collision dynamics, this study comprehensively considers the effects of different collision locations, angles, velocities, and post-collision rotational speeds and directions on the restitution coefficient during low-angle collisions. The study solves for the effects of these factors on the tangential, normal, and overall restitution coefficients from a momentum–energy perspective, providing a reference for the research on the restitution coefficient of corn kernel collisions.

MATERIALS AND METHODS

Experimental materials and Methods

The corn kernel variety examined in this study is “Zhengdan 958”.To reduce the influence of shape differences on the collision test results, trapezoidal corn kernels with a thousand-kernel weight of 316.4 g, a bottom width of 8.5±0.5 mm, a top width of 6.3±0.4 mm, a height of 12±0.8 mm, and a thickness of 3.6±0.3 mm were selected as the objects for low-angle collision tests. The names of the kernel parts are shown in Figure 1. Four hundred plump kernels were selected, and the moisture content was measured to be 12.2%.

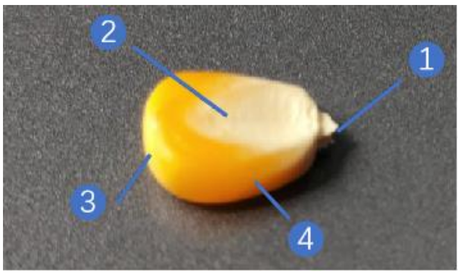

Fig. 1 - “Zhengdan 958”corn seed
1 - Top of the grain; 2 - Middle of the grain; 3 - Bottom of the grain; 4 - Side of the grain

Before the experiment, two flat plates with graduated coordinates were placed at a 90° angle on a horizontal table to simulate a three-dimensional coordinate system. After the collision, the corn kernels would move outside the collision plane. To obtain the velocity trajectory of the particles in the spatial coordinates, an interchangeable impact indentation capture paper was placed at the end of the collision path. By observing the indentations on the coordinate paper caused by the collisions of the corn kernels, the motion trajectory of the kernels outside the collision plane in space after the collision could be observed, as shown in Figure 2.

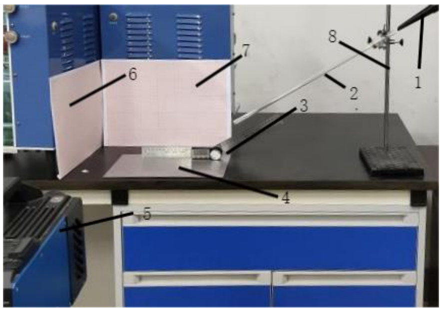

Fig. 2 - Pneumatic high-speed collision platform for agricultural products
1 - Air blower; 2 - Transparent tube; 3 - Digital protractor; 4 - Stainless steel plate; 5 - High speed camera; 6 - Dent catching paper; 7 - Graph paper; 8 - Fixing bracket

Figure 3 shows the entire process of a single corn kernel colliding with and rebounding from a wall under a high-speed camera. S1-S4 and S5-S8 are the four trajectories closest to the wall before and after the collision, respectively. Angles a and b represent the impact and rebound angles. To minimize deviation, the distances between three coordinates before and after the collision were selected and averaged to obtain the actual distance of the particle's motion. Dividing the spatial distance of the particle's motion by the time interval of the high-speed camera's capture yields the true velocity of the corn kernel. The impact angle a and the rebound angle b can be determined by recording the angle between the trajectory of the corn kernel and the wall.

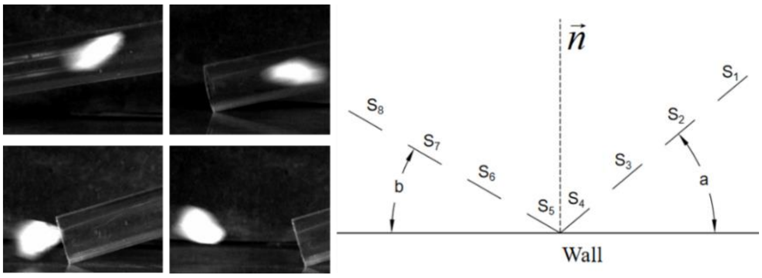

Fig. 3 - Diagram of the collision process of corn kernels

Experimental Principle and Design

Because corn kernels are non-spherical particles, different collision locations can make the post-collision trajectories of the particles very complex, with random rebounds accompanied by rotation (*Ma et al., 2020*). To measure the energy process of corn kernels during collisions, a three-dimensional spatial coordinate system is used to determine the restitution coefficient of corn kernel collisions. This approach takes into account the deformation of the corn kernel and the changes in kinetic energy due to rotation during the collision process.

This paper focuses on the changes in the motion state of corn seeds before and after collisions with the pipe wall during pneumatic conveying. The analysis is conducted based on the changes in tangential velocity, normal velocity, overall velocity, and angular velocity before and after the impact. A restitution coefficient model is employed to normalize the experimental results. Under low-angle inclined impacts, the effects of collisions on the tangential velocity of corn kernels are revealed. Therefore, this experiment needs to consider the tangential restitution coefficient, normal restitution coefficient, and overall restitution coefficient simultaneously. The characteristics of post-collision rebound in the oblique impact collision model established by Maw were used for formula derivation, and the velocity vectors during the collision process were analyzed (*Maw et al., 1976*).

Tangential restitution coefficient:

$$e_t = \frac{V_{nr}}{V_{ni}} = \frac{V_r sinb}{V_i sina} \tag{1}$$

Normal restitution coefficient:

$$e_n = \frac{V_{tr}}{V_{ti}} = \frac{V_r cosb}{V_i cosa} \tag{2}$$

In this context, V_i represents the impact velocity vector of the corn kernel, which is determined by the experimental setup and lies within the XOZ plane. V_r denotes the rebound velocity vector of the corn kernel. Given that corn kernels are non-spherical particles, even when colliding with a flat steel plate, irregular rebounds can still occur. V_{ti} and V_{ni} are the tangential and normal components of the impact velocity vector V_i, respectively, while V_{tr} and V_{ni} are the tangential and normal components of the rebound velocity vector V_r, respectively.

The elbow section is the region with the highest collision intensity in a dilute-phase pneumatic conveying pipeline, where particle-particle and particle-wall collisions are the main forms of breakage. Based on preliminary experiments, this paper investigates the breakage and motion states of collisions at angles ranging from 10 to 40°.

Two collision directions of corn kernels, top-first and bottom-first, were designed, and 80 trials were conducted for each angle. A second trial was used to ensure that the collision angle of each corn kernel deviated from the set angle by ±1°, ultimately obtaining valid experimental data for each of the four angles, consisting of 80 sets each. The speed and angle of the corn kernels before collision, the collision location of each kernel, and the rotational speed, rotational direction, displacement speed, and rebound angle of the corn kernels after collision were all documented. The experimental results were processed using fractal statistical principles, and the conditions for different collisions were summarized. The results were then subjected to fractal processing, and the Pearson correlation coefficient was calculated to draw conclusions (*Han et al., 2019*).

This paper employs air jet ejection to meet the requirement of high initial collision velocity. However, this method causes the post-collision velocity of corn kernels to be more influenced by the airflow than their actual rebound velocity. To address this issue, corn kernels were placed stationary near the collision site. The post-collision velocity of the initially stationary kernels was computed. By subtracting the velocity of the stationary kernels from that of the incident kernels, the corrected rebound velocity was obtained.

RESULTS

To address the issue that the force direction during collisions of non-spherical particles is not perpendicular, the overall and tangential restitution coefficients are introduced to assess the impact of the collision location on the restitution coefficient under different angles and initial velocities.

The impact of secondary collisions

It was observed that the probability of secondary collisions of corn kernels with the steel plate at four angles accounted for a high proportion of the total experiments and should be included in the restitution coefficient of small-angle collisions between corn kernels and the steel plate.

The essence of secondary collisions is that the rebound height of the corn kernel after the first collision is insufficient (the distance from the centroid to the next collision point does not exceed the rotational radius of the kernel). Secondary collisions manifest in two ways: The first is when the separation velocity of the corn kernel after the collision is small and the rotational velocity is large, causing the kernel to collide with the steel plate again due to rotation, during which the rotational velocity decreases and the separation velocity increases. The second scenario occurs when the corn kernel already has a relatively high initial velocity after the first collision. The secondary collision only changes the posture after rebounding (the path after rebounding, rotational state, etc.), and the impact on velocity is minimal.

Statistics show that the restitution coefficients during secondary collisions are smaller than those during primary collisions, but the differences are small: The deviation rates of the tangential, normal, and velocity restitution coefficients (calculated as the difference between the single-collision value and the combined value, divided by the combined value) are 0.21%, 0.98%, and 0.29%, respectively. Secondary collisions mainly involve the transformation of high rotational velocity into translational velocity, with the force direction primarily being normal, leading to the greatest impact on the normal restitution coefficient. Given that secondary collisions between corn kernels and the pipe wall are inevitable, the restitution coefficients of secondary collisions should be included in the overall consideration to derive a comprehensive collision restitution coefficient.

The impact of collision angle

This paper employs fractal statistical methods to summarize the patterns. The single-factor analysis indicates that under the condition of collision angles ≤40°, the tangential, normal, and velocity restitution coefficients all decrease as the collision angle increases.

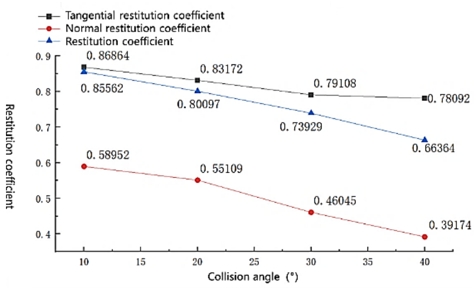

Fig. 4 - The Effect of Collision Angle on the Restitution Coefficient

By analyzing the intersection extended from three frames before and after the collision of corn kernels, it was found that there was no slip during the collision. When the collision angle is within the range of 10 - 40°, all three restitution coefficients decrease as the angle increases, with the tangential having the smallest rate of decrease and the normal having the largest rate of decrease. The reason is that as the collision angle increases, the elastic deformation of the corn kernel increases, leading to a decrease in the normal restitution coefficient. The reason for the decrease in the tangential restitution coefficient is that during the collision, there is a tangential frictional force that increases with the normal contact force, indicating that the angle has a smaller effect on the tangential restitution coefficient. The overall restitution coefficient decreases due to the decrease in both the normal and tangential restitution coefficients.

The impact of initial velocity

The tangential component of the velocity in this paper is much greater than the normal component within the 10° to 30° range. The Pearson correlation between the tangential restitution coefficient and the tangential component of the initial velocity was calculated for each of the four angles, as shown in Figure 5 and Table 1.

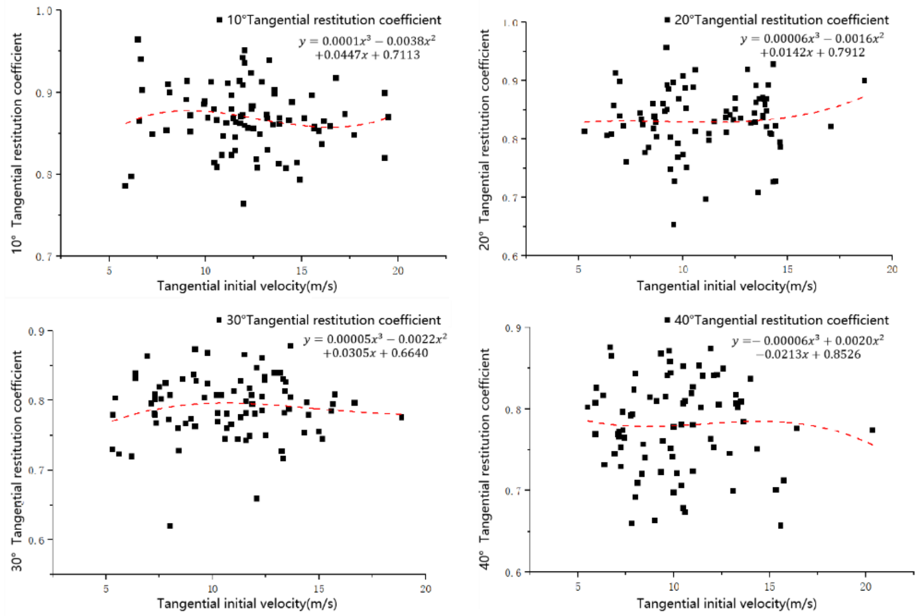

Fig. 5 - Distribution of tangential restitution coefficients at different angles

Table 1

Tangential restitution coefficient and the tangential component of the initial velocity

Collision angle	Significance level of correlation P	Degree of correlation
10	0.37224	Not correlated
20	0.64339	Not correlated
30	0.67643	Not correlated
40	0.96503	Not correlated

Based on the kinetic analysis, it can be concluded that in the case of low-angle oblique collisions, due to the small friction coefficient between the corn kernels and the steel plate and the relatively small normal impact force at low angles, according to equation (3), the effect of tangential friction can be neglected. This leads to the tangential restitution coefficient being independent of the tangential component of the initial velocity.

$$f = \mu\left(\frac{mV_r - mV_i}{\Delta t}\right) \quad (3)$$

By comparing the experimental results of the four groups of angles and analyzing the relationship between the normal restitution coefficient and the normal component of the initial velocity, it was found that at 10° and 20°, there is no definite relationship between the normal restitution coefficient of corn kernels and the normal component of the initial velocity.

At 30° and 40°, the normal restitution coefficient decreases with the increase of the normal initial velocity. The Pearson correlation between the normal restitution coefficient and the normal component of the initial velocity was calculated for the four angles, and the results are shown in Figure 6 and Table 2.

Table 2

The normal restitution coefficients and the normal components of the initial velocity for the four angles

Collision angle	Significance level of correlation P	Degree of correlation	Correlation coefficient R^2
10	0.99131	Not correlated	
20	0.11398	Not significant	
30	0.14945	Not significant	
40	0.00683	Significant	-0.30201 Weak correlation

In oblique collisions, corn kernels undergo eccentric collisions and rotation, resulting in a reduction of the normal contact force. At small angles, the normal component of the velocity is small, the normal contact force is small, and the primary effect is the generation of a torque that causes the kernel to rotate. At large angles, part of the energy loss is manifested as the contact force of normal elastic deformation, and at this time, the normal contact coefficient is significantly correlated with the normal component of the initial velocity. However, at angles of 30° and below, the normal restitution coefficient is not significantly correlated with the normal component of the initial velocity.

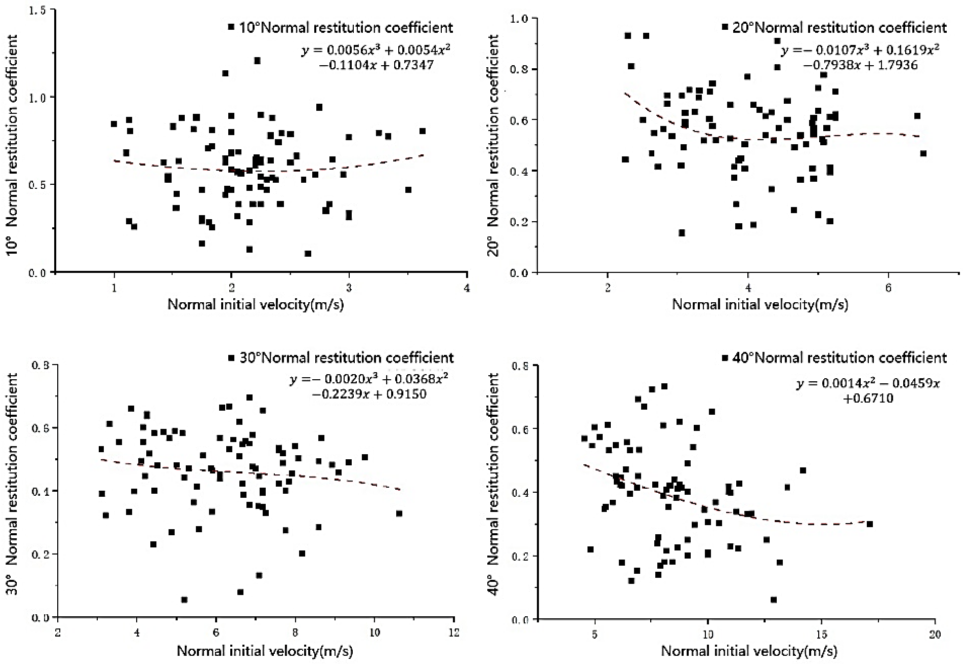

Fig. 6 - Distribution of normal restitution coefficients at different angles

The Pearson correlation between the overall restitution coefficient and the initial velocity was calculated for each of the four angles, as shown in Table 3. Based on the principles of kinematics, a significant correlation between the overall restitution coefficient and the initial velocity only appears when the collision angle is greater than or equal to 40°.

Table 3

The correlation between the overall restitution coefficient and the initial velocity for the four angles

Collision angle	Significance level of correlation P	Degree of correlation	Correlation coefficient r
10	0.41191	Not correlated	
20	0.8482	Not correlated	
30	0.79048	Not correlated	
40	0.07907	Significant	-0.20877 Weak correlation

The impact of collision location

The collision sites of corn kernels with the steel plate were divided into the head, ventral side, base, and side. The collision site at the moment of impact was recorded, and the restitution coefficients and deviations from the overall restitution coefficient at different sites and angles were statistically analyzed, as shown in Figure 7. Collisions at 10° and 20° were ignored in the analysis due to the small normal contact force and significant shape influence. The results showed that the normal restitution coefficient had the highest deviation rate and was most affected by the collision site. When the head collided, the normal restitution coefficient was lower than the overall value due to the soft and easily deformable pedicel. When the ventral side collided, the normal restitution coefficient was higher than the overall value because of the dense and hard endosperm tissue. When the side and base collided, the normal restitution coefficient was slightly higher than the overall value. The tangential restitution coefficient was greatly affected by friction and rotation, but since the friction coefficients were the same at all sites, the influence was relatively small when the angle was the same. The tangential restitution coefficient of the head was slightly lower than the overall tangential restitution coefficient, while that of the base was slightly higher. The overall restitution coefficient was less affected by the collision site.

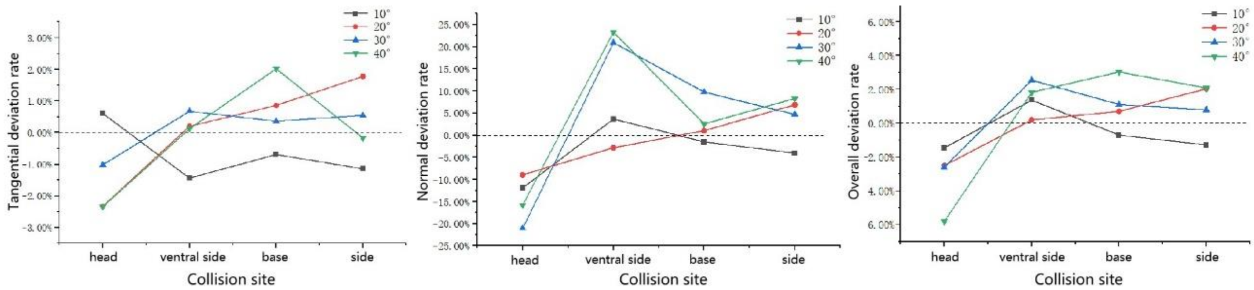

Fig. 7 - Overall restitution coefficient at different collision sites and angles

The impact of rotation after collision

In the experiment, 99.1% of the corn kernels rotated after collision. Therefore, the rotation direction and speed of the corn kernels after collision were recorded. The experimental results show that the rotation state of the corn kernels after collision is mainly related to the instantaneous posture, position, angle of the collision, and the angle between the axis through the center of mass of the kernel and the collision surface.

The kinetic energy of a rigid body in planar motion is equal to the sum of the translational kinetic energy of the center of mass and the rotational kinetic energy about the center of mass.

$$T = 1/2mv_c^2 + 1/2J_C\omega^2 \quad (4)$$

The shape of the corn kernel is approximately a trapezoidal prism, which has geometrical symmetry. Taking the x, y, and z axes through the center of mass (point o), the trapezoidal prism can rotate about the x, y, and z axes. The top edge of the trapezoidal prism is set at 6.5 mm, the bottom edge at 9.5 mm, the height at 12 mm, and the thickness at 3 mm. Using the mass projection method, the moment of inertia about the z-axis is calculated as $J_z = 9.04\times10^{-13} kg\cdot m^2$, about the y-axis as $J_y = 1.76\times10^{-12} kg\cdot m^2$, and about the x-axis as $J_x = 1.51\times10^{-12} kg\cdot m^2$. The average kinetic energy due to rotation is 2.85×10^{-5} J, and the average kinetic energy due to translation is 1.6×10^{-2} J. The ratio of rotation to translation is 561. It can be concluded that for high-speed oblique collisions of corn kernels, the kinetic energy generated by rotation can be neglected, and the kinetic energy due to translation is the dominant kinetic energy.

The impact of rotation direction

Observations revealed that after collision, corn kernels would rotate in two different directions due to the varying collision sites, as shown in Figure 8. One type of rotation occurs within the xoz plane, around an axis parallel to the y-axis, termed parallel-plane rotation (A). The other type takes place within the zoy plane, around an axis parallel to the x-axis, known as perpendicular-plane rotation (B).

Statistics indicated that, apart from the 30° angle where the proportion of co-directional rotation accounted for 53% of the total, the proportion of co-directional rotation at other angles was 33±2%. When rotating in the same direction, all three restitution coefficients were lower than when rotating in the opposite direction.

However, the ratios of the differences between the restitution coefficients in different directions and the combined restitution coefficients varied. Figure 9 shows the ratio of the difference between the restitution coefficients in the perpendicular plane and those in the parallel plane to the combined restitution coefficient. It can be seen that the tangential restitution coefficient is least affected by the rotation direction, while the normal restitution coefficient is most affected. The fluctuation in the combined normal restitution coefficient caused by counter-directional and co-directional rotations reaches 8.95%. Since all three restitution coefficients follow the order of 40° > 10° > 30° > 20°, it is concluded that the effect of rotation direction on the restitution coefficients is independent of the angle. The reason why the restitution coefficients are lower during perpendicular-plane rotation than during parallel-plane rotation remains to be investigated. The conclusion is that during low-angle oblique collisions, the tangential, normal, and overall restitution coefficients for parallel-plane rotation are all lower than those for perpendicular-plane rotation, with the normal restitution coefficient being most affected by the rotation direction.

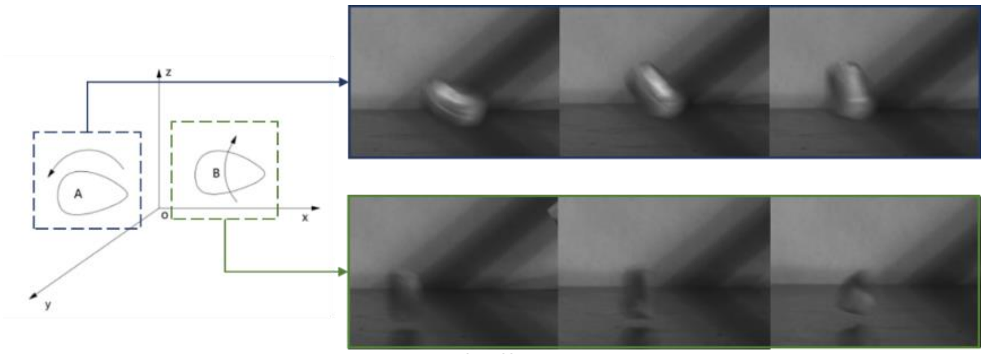

Fig. 8 - Actual images of different rotation directions

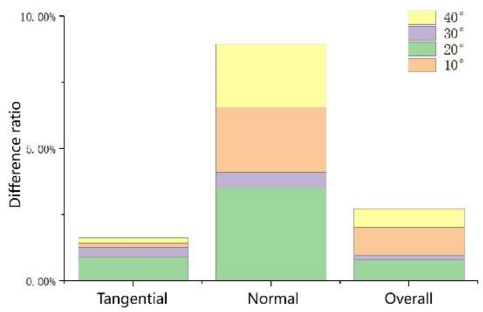

Fig. 9 - The ratio of the difference between the two directions of rotation to the combined value

The impact of rotational speed

As shown in Figure 10, when the collision angle increases, the rotational speed of the corn kernel after collision accelerates, leading to energy transfer. Although the kinetic energy generated by rotation is much smaller than that by translation, the influence of rotation on energy transfer grows as the rotational speed increases.

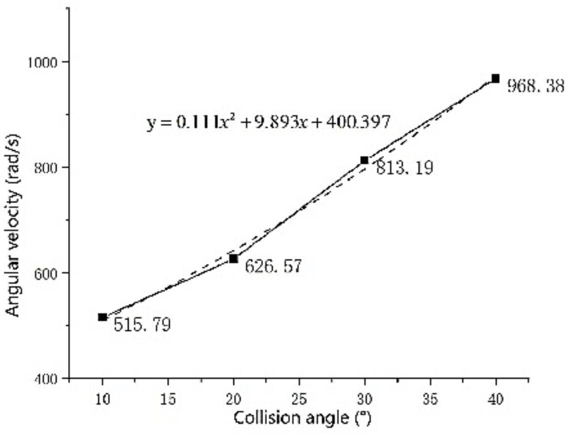

Fig. 10 - Relationship between rotational speed and collision angle

The correlation between the restitution coefficients at each of the four angles and the rotational speed was statistically calculated, as shown in Table 4.

Table 4

The restitution coefficients at each of the four angles and rotational speed

Restitution coefficient	Collision angle	Significance level of correlation P	Degree of correlation	Correlation coefficient r
Tangential	10	0.36051	Not correlated	
	20	0.16958	Not correlated	
	30	0.10069	Relatively significant	0.18143 Extremely weak correlation
	40	0.00236	Significant	0.33537 Weak correlation
Normal	10	0.55983	Not correlated	
	20	0.0194	Significant	-0.28293 Weak correlation
	30	0.0003	Significant	-0.4181 Moderate correlation
	40	0.0001	Significant	-0.4381 Moderate correlation
Overall	10	0.3415	Not correlated	
	20	0.1607	Not correlated	
	30	0.7538	Not correlated	
	40	0.9287	Not correlated	

That is, within the range of 30°~40°, the greater the rotational speed, the greater the normal restitution coefficient, while within the range of 20°~40°, the greater the rotational speed, the smaller the normal restitution coefficient, as shown in Figure 11, which illustrates the relationship between the normal restitution coefficient at 30° and the angular velocity. Since the tangential restitution coefficient increases with increasing rotational speed, while the normal restitution coefficient decreases with increasing rotational speed, there is no correlation between the overall velocity restitution coefficient and the rotational speed.

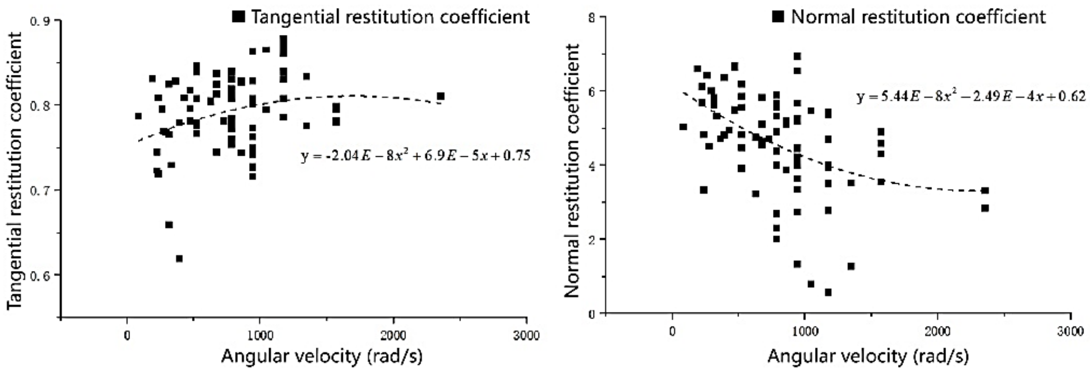

Fig. 11 - Relationship between coefficient of restitution and angular velocity at 30° collision angle

Simulation analysis

The impact analysis was conducted in ANSYS Workbench 2021 R1 using the explicit dynamics solver LS-DYNA. Following the LS-DYNA Material Selection Manual, the maize kernel was modeled as an elastic-plastic material with a density of 1120 kg/m3, an elastic modulus of 246.72 MPa, a Poisson's ratio of 0.32, and a yield strength of 37 MPa. The initial velocity of the particles was set at 21 m/s, and the collision angles were approximately 10° and 40°. An oblique impact test was conducted by filling the acceleration tube with corn kernels to obtain the results.

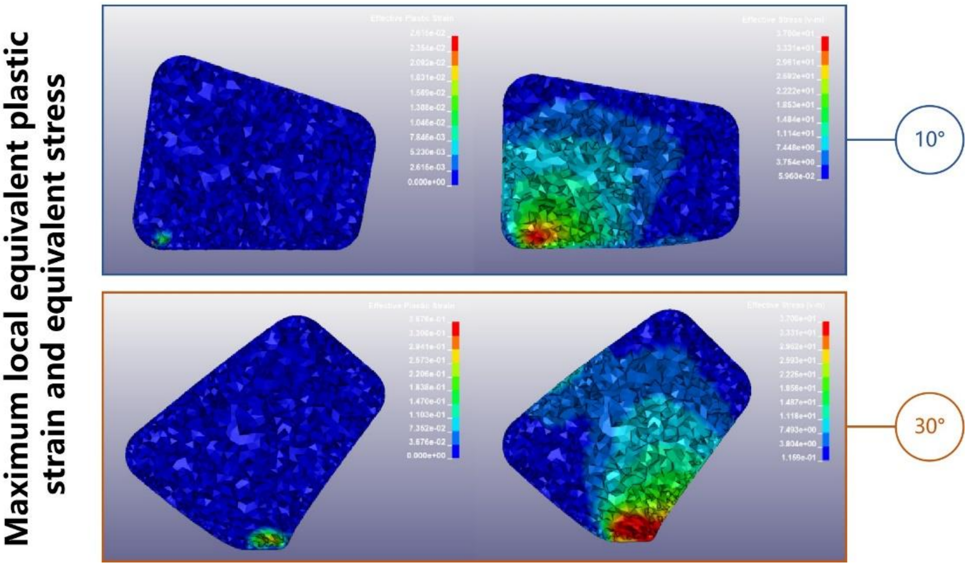

Fig. 12 - Simulation at collision angles of 10° and 30°

As can be seen from Figure 12, the distribution of the maximum equivalent plastic strain is consistent with that of the corresponding equivalent stress distribution, both being concentrated on the inner side of the collision point. The combined analysis indicates that this is due to the superposition of the reaction force from the steel plate on the corn kernel and the inertia of the corn kernel itself, resulting in a concentrated compressive stress at this location. It was found that both the maximum local equivalent plastic strain and the equivalent stress increase with the increase of the collision angle, which verifies the conclusion that the restitution coefficient decreases with the increase of the collision angle.

CONCLUSIONS

1）All three restitution coefficients decrease with increasing collision angle, with the normal coefficient being more affected by the angle than the tangential coefficient.

2）Secondary collisions mainly affect the normal restitution coefficient and should be included in the comprehensive consideration of the collision restitution coefficient.

3）The tangential restitution coefficient is independent of the tangential component of the initial velocity. The normal and overall restitution coefficients only decrease with increasing velocity when the angle is greater than or equal to 40°.

4）The collision location significantly impacts the normal restitution coefficient. When the angle is greater than or equal to 30°, the normal restitution coefficient is lower than the average value for top collisions and higher for abdominal collisions. The tangential and overall coefficients are less affected by the collision location.

5）The tangential, normal, and overall restitution coefficients are all lower for parallel-plane rotation than for perpendicular-plane rotation, with the normal restitution coefficient being most affected by the rotation direction. When the collision angle is between 30° and 40°, the tangential restitution coefficient tends to increase with increasing rotational speed. When the angle is between 20° and 40°, the normal restitution coefficient decreases with increasing rotational speed. Within the range of 10° to 40°, the overall restitution coefficient is independent of the rotational speed.

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