Frictional collision acceleration and damage of potato peel: an experimental study

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ABSTRACT
To obtain the acceleration characteristics of frictional collision between potato and rod, and reveal the mechanism of potato peel damage, a frictional collision test rig was designed to conduct single factor test and peel damage threshold test. Results showed that the maximum frictional collision acceleration (MFCA) decreased linearly with the increase of potato mass and increased linearly with the increase of initial height. The MFCA of potato colliding with the horizontal rod was smaller than that with the vertical rod, and the MFCA with the rolling rod was smaller than that with the fixed rod. The MFCA decreased in turn when potato was collided with 65Mn-rubber, 65Mn-plastic and 65Mn. The acceleration threshold of peel damage for 250 g potato was the smallest when it collided with 65Mn rod fixed in the horizontal direction from 50 mm height, which was 15.56 m/s². The acceleration threshold was the largest for the collision with 65Mn-rubber rod fixed in the vertical direction, which was 113.6 m/s². The research methods and conclusions of this article provided a basis for the analysis of potato peel damage mechanism, and also provided a reference method for researches on the peel damage of solid–like agricultural materials and food.

INTRODUCTION

Potato is an important food and cash crop in the world,[1,2] the peel and internal tissue damage caused by collision have seriously affected its sales and storage, and brought great economic losses to the potato industry.[3–5] The potato damage in harvesting and sorting is mainly caused by the collision with rod separator.[6,7] The collision between potato and rod can be divided into normal collision and frictional collision. The normal collision is easy to cause the tissue browning of potato and even cause the internal cracks, which will aggravate the decay of potato and affect its sales and storage. The frictional collision causes the peel damage of potato at the collision site, which will affect the appearance quality of potato and reduce its sales.

Scholars have done many researches on the normal collision, and the kinematic and dynamic characteristics of the collision process are mainly focused. Xie[7,8] tested the displacement and acceleration of potatoes colliding normally with rods based on a pendulum test device. Geyer[9] placed an acceleration sensor inside a potato to analyze the drop collision acceleration and its influencing factors. Rady[10] used an instrumented sphere potato dropping onto the steel rod surface to test the acceleration. Gao[11] and Cerruto[12] used the finite element method to simulate the normal collision process of potatoes with a steel plate. Some scholars had done researches on the frictional collision of agricultural materials. Ma[13] studied the physical model of frictional displacement and loads between rape stalk and non–smooth screen surface, and analyzed the drag reduction effect of different screen surfaces through reciprocating friction test. Yang[14] tested the frictional force and friction coefficient.
between apple and plexiglass or kraft paper using the digital mobile platform. Lu\textsuperscript{[15]} studied the effects of four different materials and three types of soil moisture contents on the friction coefficient of wheat and corn straw. Researches on the friction characteristics of potato peel were limited to the analysis of friction coefficient between potato and different materials by the slope method.\textsuperscript{[16–18]}

Based on these studies, there have been studies on the normal collision of potatoes and friction research of various agricultural materials, but there are few studies on the friction of potato, especially on the frictional collision and peel damage of potato colliding with rod. One of the main reasons is the lack of the potato peel frictional collision test device. Therefore, in this article, a frictional collision test rig was designed to study the collision acceleration and peel damage of potato according to the principle of single-pass pendulum scratch test.

In the late 1970s, O.Vingsbo of Uppsala University in Sweden modified the Charpy-V single-pass pendulum impact tester into the single-pass pendulum scratch tester to test the wear resistance of metal surface.\textsuperscript{[19,20]} Based on the single-pass pendulum scratch method, many researches had been done. Kennedy\textsuperscript{[21,22]} studied the scrape ability between turbine blade and sealing material. Lamy and Briscoe\textsuperscript{[23–25]} studied the wear properties of some quasi brittle materials. Li\textsuperscript{[26–29]} studied the dynamic impact wear resistance of a variety of composite metal materials.

In this article, the principle of single-pass pendulum scratch test was applied to potato peel frictional collision test. The purpose was to analyze the frictional collision acceleration between potato and rod and obtain the correlation between the acceleration and peel damage of potato. This article revealed the influence of potato mass, collision velocity and direction, rod material and rod state on the frictional collision acceleration, and provided references for potato breeding, structural design, material selection, and adjustment of working parameters of potato harvester.

**Material and methods**

**Raw materials**

Potatoes were dug out manually one day before the test from the potato planting base in Wuchuan County, Hohhot City, China. Potatoes with undamaged surfaces were selected as the experimental materials. The potatoes were sealed with the soil in black plastic bags to avoid light and stored at a room temperature of about 15°C. The variety of potato was FuRuiTe, which was widely planted in Inner Mongolia Autonomous Region. Before the test, potatoes were washed clear with cold water, and then the excess part was cut off by a knife to make each tuber mass reach the specified values.

**Frictional collision test equipment**

When the potato peel collided with the rod, the contact position and overlap distance between potato and rod needed to be adjusted dynamically. The pendulum frictional collision test rig was shown in Figure 1. An adjusting screw was designed on the top of the bracket. After loosening the screw, the supporting shaft could be moved horizontally and vertically to adjust the contact position and overlap distance. The potato was clamped at the end of the light rod and lifted to a certain height to release. The frictional collision between the potato peel and rod would occur when the potato swung close to the lowest position. The potato frictional collision tests were carried out via the test rig and an acceleration acquisition system, which included a data acquisition and an analyzer (AVANT-MI7016, Hangzhou Yiheng Technology Co., Hangzhou, China), a 1.2 g-mass acceleration sensor with the accuracy of ±1.048 mv/m/s\textsuperscript{2} and dimensions of 13 × 7.2 × 5.3 mm (1A803E, Jiangsu Donghua Testing Technology Co., Jiangsu, China) and a computer.
Testing process

The collision test apparatus is shown in Figure 2. Before the test, the potato was fixed on the clamp at the end of the light rod with adhesive tape, and the acceleration sensor was fixed on the potato surface near the collision position. Then the horizontal position of the supporting shaft was adjusted to determine the frictional collision contact position between the potato and rod. After that, the distance \((A)\) from the top of the bracket to the center of the supporting shaft was measured. The distance \((B)\) from the top of the clamp to the lowest position of the potato peel, and the distance \((C)\) from the surface of the bracket to the highest point of the rod surface were also measured. The height from the top of the bracket to its surface was 900 mm, and the height from the center of the supporting shaft to the top of the clamp was 710 mm. To make the potato and rod collide with each other, the distance between the lowest point of the potato peel and the highest point of the rod surface were adjusted to keep the overlap at 2 to 3 mm. The distance of \(A\) can be adjusted by loosening the adjusting screw to make the parameters meet the following equation.

\[
A + B + C + 710 - 900 = 2\sim3
\]  

(1)

According to the initial height of potato in the experiment, the corresponding position on the height ruler was found, and an infrared laser marking instrument (GLL5–50X, Robert Bosch Power Tools Gmbh, Stuttgart, Germany) was used for positioning. The potato was lifted to the height of the positioning line and then released to collide with the rod.
Potato collision program

The single factor test program of potato frictional collision is shown in Table 1. The test was carried out by the test equipment shown in Figure 1. The experimental factors were the potato mass, initial height, rod direction, rod state, and rod material (the coating thickness of rubber and plastic upon the 65Mn rod surface was 2 mm), and the experimental index was the maximum frictional collision acceleration (MFCA). To obtain the reliable results, ten replicates were performed for each test and the average MFCA was taken as the final result.

In order to obtain the acceleration threshold of potato peel damage, potatoes with the same mass of 250 g were collided with rods of different parameters from a height of 50 mm. Before the test, the supporting shaft was adjusted to make the overlap distance between the potato and rod increase gradually from small to large. After each collision, the potato peel was observed for damage. The MFCA was taken as the damage threshold when the potato peel was damaged for the first time. Five replicates were performed for each test, and the average MFCA was taken as the final result. The test program and results are shown in Table 2.

Results and discussion

Analysis of frictional collision acceleration curves

According to the test program in Table 1, the typical acceleration curves of potatoes were obtained, as shown in Figure 3. When the rod was fixed horizontally (Figure 3-1), the frictional collision
The acceleration increased from zero. The acceleration fluctuated in a certain range during the collision process and reached to the maximum when the lowest point of the potato peel contacted with the rod. When the potato began to break away from the rod, the acceleration decreased gradually until the signal disappeared. When the rod was fixed vertically (Figures 3-2, 3-3, 3-4 and 3-5), the acceleration curves of different rod states and materials had the similar trends. During the collision process, the frictional collision acceleration increased rapidly from zero to the maximum and then decreased rapidly to zero. Ignoring the noise signal after the collision, it can be found from the figures (Figures 3-2, 3-3, 3-4 and 3-5) that the collision contact time was obviously shorter than that when the rod was fixed horizontally (Figure 3-1). That was because when the rod was fixed vertically, the collision contact distance was shorter and the contact time was shorter correspondingly.

When the rod was fixed horizontally, the profile of the contact section between the potato peel and the rod surface was a curve and a straight line. The change of the overlap distance mainly depended on the curvature radius of the potato peel. Due to the short contact time, the curvature radius changed little, so the frictional collision acceleration only fluctuated gently in a certain range. When the rod was

| Test number | Potato mass/g | Initial height/mm | Rod direction | Rod state | Rod material | Acceleration threshold/m·s⁻² |
|-------------|---------------|-------------------|---------------|-----------|--------------|-----------------------------|
| 1           | 150           | 50                | Horizontal    | Fixed     | 65Mn         | 15.56                       |
| 2           | 200           |                   |               |           |              |                             |
| 3           | 250           |                   |               |           |              |                             |
| 4           | 300           |                   |               |           |              |                             |
| 5           | 350           |                   |               |           |              |                             |
| 6           | 250           | 30                | Horizontal    | Fixed     | 65Mn         |                             |
| 7           | 40            |                   |               |           |              |                             |
| 8           | 50            |                   |               |           |              |                             |
| 9           | 60            |                   |               |           |              |                             |
| 10          | 70            |                   |               |           |              |                             |
| 11          | 150           | 50                | Vertical      | Fixed     | 65Mn         |                             |
| 12          | 200           |                   |               |           |              |                             |
| 13          | 250           |                   |               |           |              |                             |
| 14          | 300           |                   |               |           |              |                             |
| 15          | 350           |                   |               |           |              |                             |
| 16          | 150           | 50                | Vertical      | Rolling   | 65Mn         |                             |
| 17          | 200           |                   |               |           |              |                             |
| 18          | 250           |                   |               |           |              |                             |
| 19          | 300           |                   |               |           |              |                             |
| 20          | 350           |                   |               |           |              |                             |
| 21          | 150           | 50                | Vertical      | Fixed     | 65Mn         |                             |
| 22          | 200           |                   |               |           |              |                             |
| 23          | 250           |                   |               |           |              |                             |
| 24          | 300           |                   |               |           |              |                             |
| 25          | 350           |                   |               |           |              |                             |
| 26          | 150           | 50                | Vertical      | Fixed     | 65Mn         |                             |
| 27          | 200           |                   |               |           |              |                             |
| 28          | 250           |                   |               |           |              |                             |
| 29          | 300           |                   |               |           |              |                             |
| 30          | 350           |                   |               |           |              |                             |

Table 1. Program of frictional collision tests.

| Test number | Potato mass/g | Initial height/mm | Rod direction | Rod state | Rod material |
|-------------|---------------|-------------------|---------------|-----------|--------------|
| 1           | 150           | 50                | Horizontal    | Fixed     | 65Mn         |
| 2           | 200           |                   |               |           |              |
| 3           | 250           |                   |               |           |              |
| 4           | 300           |                   |               |           |              |
| 5           | 350           |                   |               |           |              |
| 6           | 250           | 30                | Horizontal    | Fixed     | 65Mn         |
| 7           | 40            |                   |               |           |              |
| 8           | 50            |                   |               |           |              |
| 9           | 60            |                   |               |           |              |
| 10          | 70            |                   |               |           |              |
| 11          | 150           | 50                | Vertical      | Fixed     | 65Mn         |
| 12          | 200           |                   |               |           |              |
| 13          | 250           |                   |               |           |              |
| 14          | 300           |                   |               |           |              |
| 15          | 350           |                   |               |           |              |
| 16          | 150           | 50                | Vertical      | Rolling   | 65Mn         |
| 17          | 200           |                   |               |           |              |
| 18          | 250           |                   |               |           |              |
| 19          | 300           |                   |               |           |              |
| 20          | 350           |                   |               |           |              |
| 21          | 150           | 50                | Vertical      | Fixed     | 65Mn         |
| 22          | 200           |                   |               |           |              |
| 23          | 250           |                   |               |           |              |
| 24          | 300           |                   |               |           |              |
| 25          | 350           |                   |               |           |              |
| 26          | 150           | 50                | Vertical      | Fixed     | 65Mn         |
| 27          | 200           |                   |               |           |              |
| 28          | 250           |                   |               |           |              |
| 29          | 300           |                   |               |           |              |
| 30          | 350           |                   |               |           |              |

Table 2. Program and result of frictional collision damage threshold tests.
fixed vertically, the profile of the contact section between the potato peel and the rod surface was a curve and an arc. During the collision process, the overlap distance changed quickly, so that the frictional collision acceleration fluctuated greatly.

**Effect of potato mass and rod direction on MFCA**

According to the test program in Table 1 (test number: 1-10), the MFCA curves were obtained when the rod was fixed in both the horizontal and vertical directions (Figure 4). The MFCA decreased linearly with the increase of potato mass. Under the same conditions, when the potato was collided with the rod fixed in the vertical direction, the MFCA was larger than that of the horizontal direction. The reason was that the contact area between the potato peel and the horizontal rod was smaller than that of the vertical rod. And the frictional force increased when the contact area increased, which led to the larger MFCA.
Both Xie\textsuperscript{[7]} and Geyer\textsuperscript{[9]} placed the acceleration sensors inside potatoes to test the normal collision acceleration. Results found that the larger the potato mass was, the smaller the maximum acceleration would be. It was showed that the maximum acceleration had the same trends for potatoes in both the normal and the frictional collision.

\textit{Effect of initial height on MFCA}

The effect of the initial height on the MFCA is shown in Figure 5. The MFCA increased linearly with the increase of the initial height. When the contact overlap distance was the same, the higher the initial height was, the larger the collision contact velocity and the shorter the contact time would be. So, the MFCA became larger with the increase of the initial height. Researchers had also found similar results when analyzing the characteristics of the maximum acceleration for potatoes and rods in the normal collision.\textsuperscript{[7,10]}

\textit{Effect of rod state on MFCA}

The effect of rod state on the MFCA is shown in Figure 6. The MFCA decreased with the increase of potato mass no matter the rod was fixed or rolling. With the same potato mass, the MFCA of the rolling rod was smaller than that of the fixed rod. The rod surface was subjected to both normal and tangential forces during the frictional collision process. When the rod was not fixed, the tangential force made the rod roll and the friction between the potato and rod was rolling friction. When the rod was fixed, there

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{Curve of the MFCA with the initial height.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure6.png}
\caption{Curves of the MFCA with the potato mass in different rod states.}
\end{figure}
was always sliding friction between the potato and rod. Under the same conditions, the rolling friction force was smaller than that of the sliding friction. Therefore, the MFCA of the rolling rod was smaller than that of the fixed rod. If the rod of the potato soil separating device of potato harvester was designed in the rolling state, it would be beneficial to reduce the peel damage of potatoes during the harvest process.

**Effect of rod material on MFCA**

The effect of rod material on the MFCA is shown in Figure 7. The MFCA decreased linearly with the increase of potato mass in the three types of materials. The MFCA was the smallest when the potato was collided with 65Mn rod and the MFCA was the largest with 65Mn-rubber rod. The elastic modulus of rubber, plastic and 65Mn increased in turn, and their abilities to resist elastic deformation increased gradually. When the potato was collided with 65Mn-rubber, the elastic deformation of rubber was large, which increased the contact area and led to a larger tangential force, so the MFCA became larger. When the potato was collided with 65Mn rod, the rod deformation was very small because of the large rod stiffness. Therefore, the collision contact area between the potato and rod was very small, which caused the smaller tangential force and the MFCA. Xie\(^7\) found that the damaged area was the smallest but the maximum acceleration was the largest during potato normally colliding with 65Mn-rubber, compared to 65Mn and 65Mn-plastic.

**Analysis of acceleration threshold of potato peel damage**

According to the results in Table 2, when the potato with a mass of 250 g was collided with the rod from the height of 50 mm, the acceleration threshold of potato peel damage was the smallest with the 65Mn rod, which was fixed horizontally, and that was the largest with the 65Mn-rubber rod, which was fixed vertically. The acceleration threshold of the rolling rod was larger than that of the fixed rod.

The results showed that the movement of potato along the rod on the separating device was easier to the damage of potato peel than the movement perpendicular to the rod. Proper control of the acceleration of potato moving along the rod direction during the harvest can reduce the peel damage. It would be helpful to reduce the potato peel damage if the rod on the separating device was designed in the rolling state or covered with a certain thickness of rubber. Similar researches had also found that the cushioning materials performed well in reducing the impact damage of potatoes.\(^7,9,30\)

![Figure 7. Curves of the MFCA with the potato mass in different rod materials.](image-url)
Conclusion

In the process of mechanized harvesting, the frictional collision between the potato and rod is easy to cause the peel damage of potato, which not only seriously affects the appearance and quality of potato, but also restricts the development of potato harvester. In this article, a pendulum frictional collision test rig was designed and developed to test the acceleration between the potato and rod. The effects of potato mass, initial height, the direction, state and material of rod on the MFCA and damage threshold acceleration of potatoes were studied. The results found that the MFCA decreased linearly with the increasing potato mass but increased linearly with the increasing potato initial height. The MFCA was affected by the direction, state and material of the rod. Compared to the rolling rod, or the 65Mn and 65Mn-plastic rod, or compared to the horizontal rod, the MFCA would be larger if the rod was fixed, or the rod material was 65Mn-rubber, or the potato was collided with rod along the vertical direction. The range of acceleration threshold for the peel damage of 250 g potato from 50 mm height was 15.56 ~ 113.6 m/s². When the potato was collided with 65Mn rod fixed in the horizontal direction, the acceleration threshold was the smallest and the peel damage was most likely to occur. When the potato collided with the fixed 65Mn-rubber rod in the vertical direction, the acceleration threshold was the largest and the peel damage was least likely to occur. The experimental equipment and test method in this article provided a feasible way for the research of potato peel frictional collision acceleration characteristics. The results provided a data basis for further research of potato peel damage mechanism, and also provided a reference for low damage harvest optimization design of potato mechanized harvesting equipment. This article was also beneficial to the similar researches of other agricultural materials and food.

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