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Analysis and Experiment on the Movement Process of Potato on a Swing Separating Sieve

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Abstract: The movement process of a potato relative to the swing-separating sieve is the result of a coupling effect of the kinematical characteristics of the separating sieve and potato. To understand the movement process of potato relative to the swing-separating sieve, experiments were designed to capture the relative motion images of potato on the separating sieve at different crank angular velocities. Then, the mathematical model of the relative velocity of potato on the separating sieve was established. Based on the model, the movement process of the potato was analysed. When the crank angular velocity was 19.625 rad/s, the movement process of the potato relative to the separating sieve mainly included forward sliding, flying, and forward sliding as well as backward sliding and flying and presented as a continuous process. When the crank angular velocity was 23.55 rad/s, the movement process of the potato relative to the separating sieve was also a continuous process and principally consisted of forward sliding and flying as well as backward sliding and flying. The result from the theoretical analysis was consistent with the relative motion images of potato from the experiments. Thus, this study could be helpful to design optimal parameters of a separating sieve.

Keywords: Potato, Swing Separating Sieve, Movement Process, Relative Velocity

1. Introduction

The chain swing sieve potato digger is widely used in the Midwest area of China. The swing-separating sieve is the key component of the chain swing sieve potato digger to separate potatoes and soil [1, 2]. When the swing-separating sieve is working, the mixture of potatoes and soil moves relative to the separating sieve. Thus, soil is broken up and falls off the separating sieve, while potatoes are conveyed to the end of the separating sieve and then drop onto the ground [3, 4]. The motion characteristics of the potato, the harvested product, directly affect the performance of the separating sieve. In recent years, many researchers have explored the motion characteristics of potatoes on the separating sieve. Yang [2] and Gu [5] used dynamic analysis methods to investigate the relationships among track, velocity, acceleration of potatoes and the parameters of a separating sieve. Liu [6] implanted a miniaturized triaxial acceleration measuring unit into potato tubers and obtained the change of potato acceleration with the changed crank velocity and sieve inclination of a separating sieve. Su [1] and Xie *et al.* [7] studied the motion characteristics of potatoes at different crank velocities and sieve inclinations of a separating sieve, which included acceleration, velocity, distance and motion time. The above research mainly investigated the motion characteristics of potatoes, such as acceleration, velocity and motion time. A few studies have reported the movement process of potatoes on a swing separating sieve when the separating sieve is working in the field. Additionally, very few articles discussed the causes of this potato movement process.

Related studies have been published regarding the movement process of grain and minerals on the separating sieve [8-13]. These studies showed that materials would have three states of motion: static, sliding and flying. When the separating sieve works, the flying state of the mixture of potatoes and soil helps break up the soil. A higher soil break-up rate could lead to an outstanding separating performance. At the same time, it can also cause severe bruising of potatoes. Thus, more information of such a process could be useful for designing optimal parameters of the separating sieve. Therefore, the objectives of this study were aimed to investigate the movement process of potatoes and provide a quantitative explanation for this process.

2. Materials and Methods

2.1. Machine Description

The prototype of the 4SW-170 potato digger (Figure 1) is mainly composed of a body frame, digging shovel, elevating chain and swing-separating sieve. The main components of the swing-separating sieve include a transmission shaft, gearbox, sprocket drive mechanism, rotation shaft, front swing link, rear swing link, sieve inclination adjusting mechanism, slide plate, upper sieve and lower sieve. The structure parameters of the separating sieve detailedly are given in Table 1.

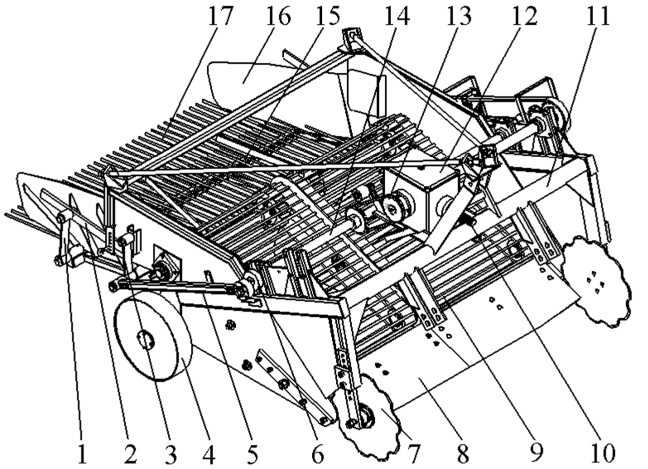


Figure 1. *Overall structure of potato digger: 1, Rear swing link; 2, Sieve inclination adjusting mechanism; 3, Front swing link; 4, Wheel; 5, Connecting rod; 6, Crank; 7, Soil cutting disc; 8, Digging shovel; 9, Elevating chain; 10, Transmission shaft; 11, Frame; 12, Reducer; 13, Sprocket drive mechanism; 14, Rotation shaft; 15, Upper sieve; 16, Side plate; 17, Lower sieve.*

Table 1. *Structure parameters of separating sieve.*

Parameter	Value
Crank radius (mm)	35
Length of connecting rod (mm)	985
Length of front swing link (mm)	230
Length of rear swing link (mm)	270
Length of separating sieve (mm)	1 100
Width of separating sieve (mm)	1 700
Vibrating direction angle (°)	10.9
Inclination of sieve surface (°)	7.7

When the potato digger works, a mixture of potatoes and soil is dug up by the digging shovel and is transported to the swing-separating sieve by the elevating chain. The crank rotates in the counter-clockwise direction to drive the separating sieve to swing forwards and backwards, which causes the soil to break up and fall off. Potatoes are conveyed to the end of the separating sieve and then drop onto the ground. The aboved steps are the working principle of the swing separating sieve.

2.2. Experimental Condition

The experiments were conducted at the Qian Naimoban village in Hohhot, Inner Mongolia Autonomous Region of China in October of 2015. The planting method used was flat planting. The soil was sandy. The average moisture content of the soil was 9.42% and the measured soil thinkness ranged from 0 to 300 mm. The plant spacing and row spacing respectively were 350 mm and 800 mm. The variety of potato was Kexin No. 1, which was widely cultivated in the Midwest of China. Note that potato seedlings and weeds were removed prior to testing.

2.3. Design of Testing System

The experiments were designed to capture the relative motion images of a potato on the separating sieve. The employed testing system consisted of a high-speed camera (Phantom Miro 2, Vision Research, USA) and a computer. To acquire the relative motion images of a potato, the high-speed camera was connected to the potato digger frame through a bracket during the separating sieve being working. A scale plate was mounted on the side plate of the separating sieve to detect the change in movement of a potato relative to the separating sieve.

The relative motion images of the potatoes were captured simultaneously when the swing separating sieve worked steadily [14]. The tests at each crank angular velocity were repeated three times. The acquired relative motion images were saved on the computer. The relative motion images of the potatoes were played back by the Phantom video player.

3. Kinetic Analysis of Separating Sieve and Potato

3.1. Kinetic Analysis of Separating Sieve

The separating sieve structure is shown in Figure 2. The sieve surface *BC* is hinged on the frame by the front swing bar *BE* and back swing bar *CD*. And the crank *OA* drives the link *AB* to push the sieve surface *BC* forwards and backwards. The movement trajectory of the sieve surface is simplified to a straight line according to the simulation results in Adams software. According to the simulation results, the positive direction of the *S*-axis was the vibration direction of the sieve surface.

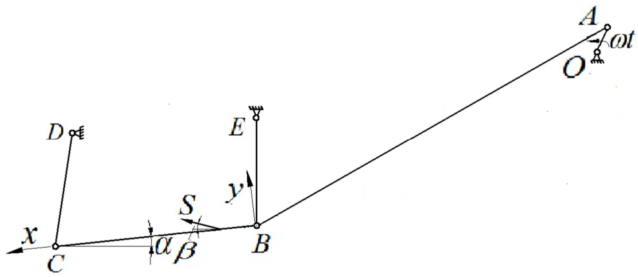


Figure 2. *Structure diagram of separating sieve.*

The displacement of the separating sieve at any time can be obtained by Equation (1):

$$s = r\sin\omega t \tag{1}$$

where *s* is the displacement of the separating sieve, *r* is the crank radius, ω is the crank angular velocity and *t* is time.

The velocity and acceleration of the sieve surface can be defined with the following Equations (2) and (3):

$$v = r\omega \cos \omega t \tag{2}$$

$$a = -r\omega^2 \sin \omega t \tag{3}$$

where v is the velocity of the separating sieve, and a represents the acceleration of the separating sieve.

The rectangular coordinate system is established, where the *x*-axis points to the separating sieve tail. Geometry includes the horizontal and vertical components of a, which are designated a_x and a_y, respectively:

$$a_x = -r\omega^2 \sin \omega t \cos(\beta + \alpha) \tag{4}$$

$$a_y = -r\omega^2 \sin \omega t \sin(\beta + \alpha) \tag{5}$$

where α is the sieve inclination, and β is the vibrating direction angle of the separating sieve.

Equations (4) and (5) show that the chief factors influencing the acceleration of the separating sieve are the crank radius *r*, the sieve inclination α, the vibrating direction angle β and the crank angular velocity ω.

According to the preliminary results, the kinematical characteristics of the separating sieve were influenced by uneven ground and tractor traction when the separating sieve worked in the field. Therefore, in order to accurately analyse the movement process of a potato relative to the separating sieve, the correction coefficient should be added into the equation, making Equations (4) and (5):

$$a_x = -k_1 r\omega^2 \sin \omega t \cos(\beta + \alpha) \tag{6}$$

$$a_y = -k_2 r\omega^2 \sin \omega t \sin(\beta + \alpha) \tag{7}$$

where k_1 is the correction coefficient of the acceleration of the separating sieve in the *x*-direction, which according to the preliminary results was k_1=1.161; and k_2 is the correction coefficient of the acceleration of the separating sieve in the *y*-direction, which according to the preliminary results was k_2=3.02 [15].

3.2. Kinetic Analysis of Potato

It is known from previous research that the potato slides relative to the separating sieve before flying away from the sieve surface [16, 17]. Therefore, the kinetics of the potato is first analysed when it slides relative to the separating sieve. Second, the kinetics of the potato is analysed when it flies away from the separating sieve.

3.2.1. Basic Assumption

To facilitate the theoretical analysis, it is necessary to make the following assumptions:

(1) The elasticity of the potato, implicated root remnants and air resistance are ignored.

(2) The mutual extrusion, collision and self-tumbling of the potatoes are ignored, and one potato is considered one particle.

3.2.2. Kinetic Analysis During Potato Sliding

When the potato slides relative to the separating sieve, the force analysis of the potato is shown in Figure 3.

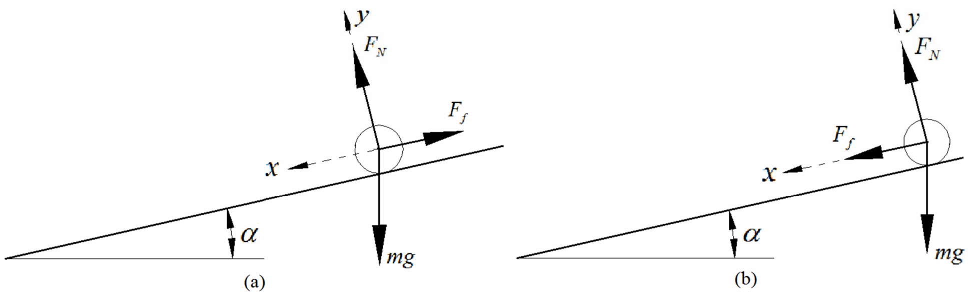


Figure 3. *Force analysis during potato forward and rearward sliding relative to the separating sieve: (a) Forward sliding, (b) Rearward sliding.*

From Figure 3, the kinetic equations of the potato are shown in the following:

$$m(a_{x_{1,2}} + a_x) = mg \sin \alpha \mp F_f \tag{8}$$

$$ma_y = F_N - mg \cos \alpha \tag{9}$$

$$F_f = \mu F_N \tag{10}$$

where $a_{x_{1,2}}$ is the acceleration of the potato when it slides relative to the separating sieve, μ is the sliding friction coefficient between the potato and the separating sieve, F_f is the friction force between the potato and the separating sieve, F_N is the support force of the separating sieve on the potato, *m* is the mass of the potato, and *g* is the gravitational acceleration.

3.2.3. Conditions for the Initiation of Potato Sliding

Substitute the parameters of the separating sieve into Equations (6)~(10) and obtain the curves of a_x, $g \sin \alpha - F_f / m$ and $g \sin \alpha + F_f / m$, as shown in Figure 4.

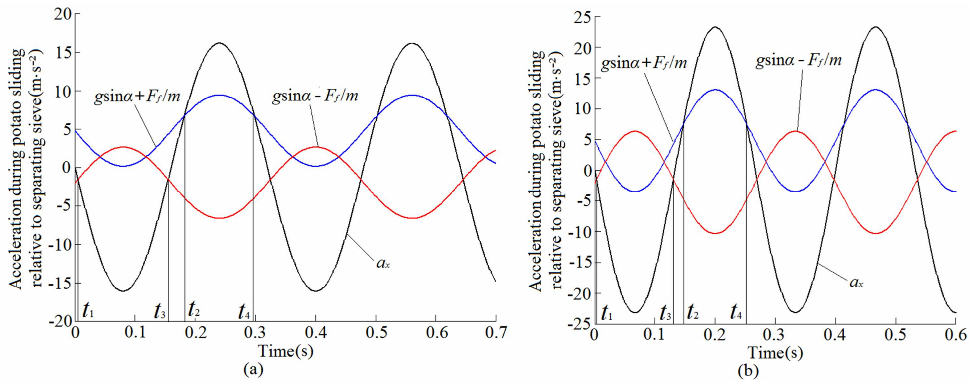


Figure 4. *Acceleration curves during potato sliding relative to separating sieve: (a) Crank angular velocity is 19.625 rad/s, (b) Crank angular velocity is 23.55 rad/s.*

Forward sliding of the potato may be initiated when a_x is equal to or greater than $g\sin\alpha - F_f/m$. Similar conditions are applied to the initiation of backward sliding, which may occur if $a_x \ge g\sin\alpha + F_f/m$. As a result, the potato may start to slide forwards within the time range of t_1 and t_3; the potato may start to slide backwards within the time range of t_2 and t_4.

3.2.4. Kinetic Analysis During Potato Flight

The critical condition for potato flight away from the separating sieve is F_N=0, which is:

$$k_2 r\omega^2 \cos\omega t \sin(\beta+\alpha) = g\cos\alpha \tag{11}$$

The time of the potato flying away from the separating sieve, which is denoted by time t_0, can be obtained by Equation (11).

After substituting the parameters of the separating sieve into Equations (6)~(10), the theoretical initial time t_1 was obtained, with t_1 less than t_0. Therefore, the potato may exhibit forward sliding motion between t_1 and t_0.

The kinetic equations during the potato flight are:

$$m(a_x' + a_x) = mg\sin\alpha \tag{12}$$

$$m(a_y' + a_y) = -mg\cos\alpha \tag{13}$$

where a_x' is the relative acceleration of the potato in the x-direction during the potato flight, and a_y' is the relative acceleration of the potato in the y-direction during the potato flight.

The relative accelerations of the potato are:

$$a_x' = k_1 r\omega^2 \sin\omega t\cos(\beta+\alpha) + g\sin\alpha \tag{14}$$

$$a_y' = k_2 r\omega^2 \sin\omega t\sin(\beta+\alpha) - g\cos\alpha \tag{15}$$

The relative velocities of the potato can be obtained by Equations (16) and (17):

$$v_x' = v_{x,t_0} - k_1 r\omega\cos(\beta+\alpha)(\cos\omega t - \cos\omega t_0) + g(t-t_0)\sin\alpha \tag{16}$$

$$v_y' = -k_2 r\omega\sin(\beta+\alpha)(\cos\omega t - \cos\omega t_0) - g(t-t_0)\cos\alpha \tag{17}$$

where v_x' is the relative velocity of the potato in the x-direction during the potato flight, v_y' is the relative velocity of the potato in the y-direction during the potato flight, and v_{x,t_0} is the relative velocity of the potato in the x-direction at time t_0. The relative displacement of the potato in the y-direction during the potato flight is given by the followed formula:

$$s_y' = k_2 r\omega\sin(\beta+\alpha)(t-t_0)\cos\omega t_0 - k_2 r\sin(\beta+\alpha)(\sin\omega t - \sin\omega t_0) - \frac{1}{2}g(t-t_0)^2\cos\alpha \tag{18}$$

When relative displacement of the potato in the y-direction during the potato flight $s_y' = 0$, the potato returns to the separating sieve, and the returning time is indicated by t'. The coefficient of restitution was assumed to be zero, which implies that the loss of energy is maximal. Kong *et al.* [17] also made this same assumption. Thus, the relative velocity of the potato in the y-direction after impact is zero: $v_y'(t'+\Delta t) = 0$. The relative velocity of the potato in the x-direction after impact is calculated by the following equations (19):

$$v_x'(t'+\Delta t) = \begin{cases} 0, \left|v_x'(t')\right| \le -\mu v_y'(t') \\ v_x'(t') + \dfrac{v_x'(t')}{\left|v_x'(t')\right|}\mu v_y'(t'), \left|v_x'(t')\right| > -\mu v_y'(t') \end{cases} \tag{19}$$

where $v_x'(t')$ is the relative velocity of the potato in the x-direction at time t', $v_y'(t')$ is the relative velocity of the potato in the y-direction at time t', and $v_x'(t'+\Delta t)$ is the relative velocity of the potato in the x-direction after impact.

4. Movement Process of Potato Relative to Separating Sieve

4.1. Theoretical Results of Movement Process

The parameters of the separating sieve were substituted into Equations (16)~(19), and the beginning of the potato sliding forward was assumed to be the theoretically initial time t_1. The relative velocity curves of the potato in the *x*-direction were plotted by using Matlab software (Matlab 13.0, Mathworks, USA), as shown in Figure 5.

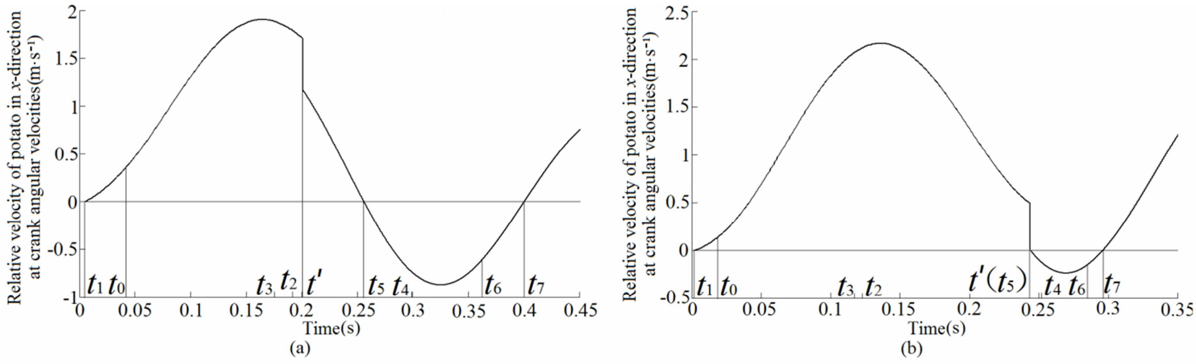


Figure 5. *Relative velocity curves of the potato in the x-direction: (a) Crank angular velocity is 19.625 rad/s, (b) Crank angular velocity is 23.55 rad/s.*

When the crank angular velocity is 19.625 rad/s (Figure 5a), the potato starts to slide forwards at the theoretically initial time t_1, until such time t_0 as F_N equals zero, at which point the potato first flies away from the separating sieve. The potato continues to fly until the relative displacement in the *y*-direction is equal to zero at time t'. According to Equation (19), the relative velocity of the potato in the *x*-direction is 1.169 m/s and greater than zero. Then, the potato continuously slides forwards until its relative velocity is again zero at time t_5. As shown in Figure 5 (a), when time t_5 lies between t_2 and t_4, the potato immediately starts to slide backwards. This backward sliding continues until F_N is again equal to zero at time t_6, at which point the potato flies away from the separating sieve. The relative velocity of potato in the flying phase turns to a positive value from a negative value at time t_7. In summary, the movement process of the potato relative to the separating sieve is a continuous process, and generally includes forward sliding, flying, and forward sliding, as well as backward sliding and flying.

When the crank angular velocity reaches 23.55 rad/s (Figure 5b), the potato starts to slide forwards at the theoretically initial time t_1, until such time t_0 as F_N equals zero, at which point the potato first flies away from the separating sieve. The potato continues to fly until the relative displacement in the *y*-direction is equal to zero at time t'. According to Equation (19), the relative velocity of the potato in the *x*-direction at time t' is zero. When time t' lies between t_2 and t_4, the potato immediately starts to slide backwards. This backward sliding continues until F_N is again equal to zero at time t_6, at which point the potato flies away from the separating sieve. The relative velocity of the potato during the flying process turns to a positive value from a negative value at time t_7. In summary, the movement process of the potato relative to the separating sieve is a continuous process and includes forward sliding and flying, and as well as backward sliding, and flying.

The flying motion of the material can be divided into two types: slight flying and strong flying. The slight flying has a longer forward sliding time, while the forward sliding of strong flying time is relatively short [18]. As shown in Figure 5, when the crank angular velocity is 19.625 rad/s, the motion state of the potato is slight flying. When the crank angular velocity is 23.55 rad/s, the motion state of potato becomes strong flying. The strong flying could promote separation of the potato and soil, but this phenomenon would also aggravate the damage rate of potato. On the other hand, the slight flying would reduce the potato damage rate [1, 2]. Therefore, the potato in the appropriate motion state can effectively solve the contradiction between obvious rate and abrasion rate in the future.

If the returning moment is in the time zone of non-flying, the flying motion of the material will be a periodic flying motion [18]. From Figure 5, under different crank angular velocities, if the returning moment of the potato at the time ranges between t_2 and t_4, it shows that the flying motion of the potato is a periodic throwing motion.

By comparing the relative velocity curves of the potato in the *x*-direction (Figure 5), the differences among them can be determined and analysed as follows.

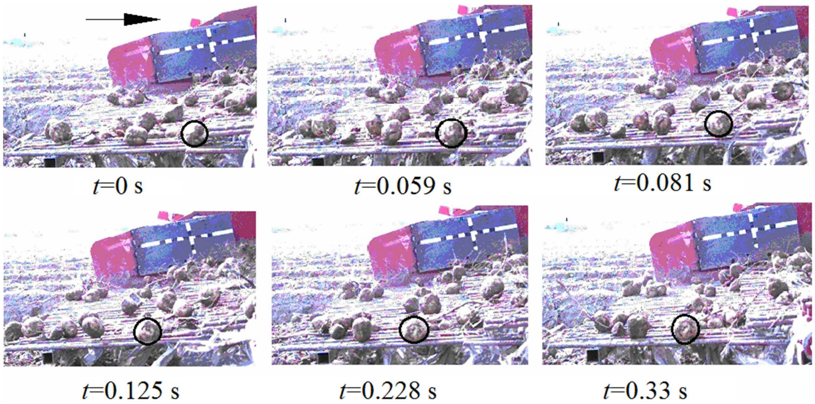
First, under different crank angular velocities, the area enveloped by the time axis and its upper curve is greater than that enveloped by the time axis and its lower curve. Corresponding, the forward distance that a potato moves relative to the separating sieve is defined as the upper area subtracted by the lower area. Obviously, the forward distance that a potato moves relative to the separating sieve is a positive value. Therefore, these two crank angular velocities of the separating sieve satisfy the requirement for transporting the potato to the sieve tail.

Second, the forward distance when the crank angular velocity is 19.625 rad/s is less than that forward distance when the crank angular velocity is 23.55 rad/s. This result indicates that the performance of the forward transportation of the separating sieve in the former is weaker than that in the latter. Guo *et al.* [10] believed that with the increase of the crank angular velocity, the transportation speed of the material will increase, which is consistent with these results.

4.2. Relative Motion Images of Potato

To compare the theoretical movement process with the experimental movement process of the potato, the relative motion images of the potato shown in Figure 6 and Figure 7 were examined.

When the experimental crank angular velocity becomes 19.625 rad/s (Figure 6), the potato starts to slide forwards at t=0 s until t=0.059 s, at which time the potato first flies away from the separating sieve. At t=0.081 s, the potato reaches the highest position, then falls to the separating sieve at t=0.125 s. When the relative velocity of the potato in the x-direction is zero, the potato slides forwards after it falls to the sieve surface until t=0.228 s. Subsequently, the potato begins to slide backwards. This backward sliding continues until t=0.33 s, at which point the potato flies away from the separating sieve. In this experiment, the potato mainly experiences forward sliding, flying, and forward sliding, as well as backward sliding and flying. This experimental movement process of the potato relative to the separating sieve is consistent with the theoretical movement process.



Note: the marked potato is in the black circle, the machine forward direction is indicated by the arrow, as same to Figure 7.

Figure 6. *Relative motion images of potato on separating sieve when crank angular velocity is 19.625rad/s.*

When the experimental crank angular velocity is 23.55 rad/s (Figure 7), the potato starts to slide forwards at t=0 s until t=0.079 s, at which time the potato first flies away from the separating sieve. At t=0.128 s, the potato reaches the highest position, then falls to the separating sieve at t=0.186 s. The potato slides backwards after it falls to the sieve surface until t=0.321 s. At this time, the potato flies away from the separating sieve and reaches the highest position at t=0.358 s. In this experiment, the potato undergoes forward sliding and flying, as well as backward sliding and flying. This experimental movement process of the potato relative to the separating sieve is consistent with the theoretical movement process.

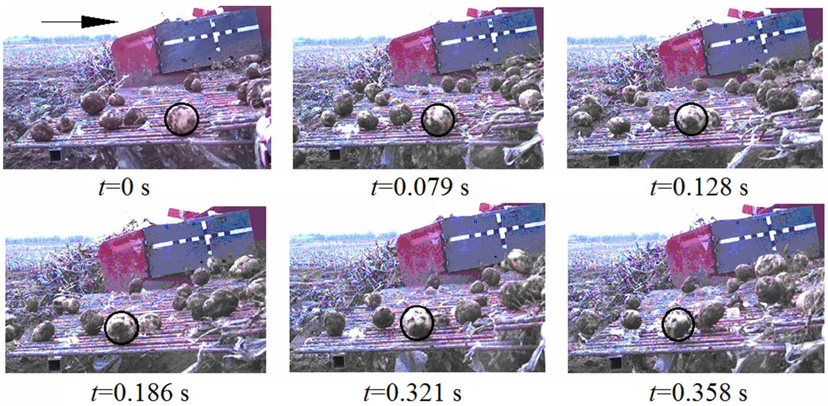


Figure 7. *Relative motion images of potato on separating sieve when crank angular velocity is 23.55rad/s.*

By comparing Figure 6 and Figure 7, the following conclusions can be reached: the forward distance when the crank angular velocity is 23.55 rad/s is greater than this distance when the crank angular velocity is 19.625 rad/s. This result is the same as the theoretical result.

The motion time of a potato relative to the separating sieve in this experiment is different from the theoretical time. According to Soldinger [16], the rolling and natural frequencies of materials could cause a difference between experimental and theoretical values. Perhaps, this could be due to the elasticity and shape of the potato or the sand coerced in the potato and sieve surface.

5. Conclusion

In this paper, the relative velocity formula of a potato was deduced. Then, the relative velocity curves of potato were plotted by Matlab software. According to the relative velocity curves of potato, the movement process of the potato relative to the separating sieve at different crank angular velocities was analysed, and the process was verified by relative motion images of the potato. It can be concluded that: when the crank angular velocity is 19.625rad/s, the movement process of potato relative to the separating sieve is a continuous process, includes forward sliding, flighting, forward sliding, and rearward sliding, flighting. When the crank angular velocity is 23.55rad/s, the movement process of potato relative to the separating sieve is a continuous process, includes forward sliding, flighting, and rearward sliding, flighting. These results provide the theoretical basis for the analysis of the kinematical characteristics of potatoes relative to the separating sieve and provide a reference for optimizing the parameters of the separating sieve.

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