Experiment on mechanical properties of processing tomatoes and theoretical study of fruit-seedling separation

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Abstract: The working object of fruit-seedling separation mechanism is tomato vines after harvesting. In order to optimize the parameters of a fruit-seedling separation mechanism, in this paper, the physical and biological characteristics of tomato variety liger 87-5 were tested and obtained that the equatorial diameter of the tomatoes was among 27-51 mm, the vertical diameter was among 28-45 mm, and fruit weight was among 19-104 g. Since the pericarp hardness of tomatoes is related to fruit size and maturity, after pericarp hardness testing of the tomatoes, the transverse damage force of liger 87-5 was among 24.2-67.1 N, and vertical damage force was among 28.6-75.3 N, the average value of pericarp hardness was 2.86 kg/cm^2. The biological force between fruit and seedling should be overcome in separation, and test results showed that when the fruit angle was 90°, the maximum separating biological force was 15.8 N, the average transverse damage force of fruit was 46.9 N, and the vertical damage force was 55.2 N. The study can provide a theoretical basis for the design of fruit-seedling separation machinery.

Keywords: processing tomatoes; fruit-seedling separation; fruit damage force; fruit-seedling separation force

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1 Introduction

The processing tomato variety liger 87-5 in China was selected in this study, because it has excellent growing, anti-crack, and anti-pressure properties, also tolerant to storage, outstanding in stress resistance and disease resistance. In all, it is a fine variety for mechanized harvesting (Liu et al., 2016 and Wang et al., 2015). Liger 87-5 variety is widely cultivated, since it has practical significance as the research object. Fruit-seedling separation is a key point in the mechanized harvesting of liger 87-5 (Li et al., 2012 and Wang et al., 2015). In order to ensure smooth fruit-seedling separation, the design of mechanical structure should take pericarp hardness of the fruit into consideration to minimize fruit damage rate; at the same time, it should improve the fruit-seedling separation rate.

Related parameters of the biophysical characteristics of tomatoes were measured, and the measured data served as a reference for analyzing the mechanical process of fruit-seedling separation. During the separation process, in order to overcome the biological forces between the plant and the fruit, the tomatoes are subjected to the mechanical energy provided by the mechanical parts of the separation device, and finally fall off from the vine. The mechanical force of the fruit-seedling separation device and the biophysical properties of tomatoes as well as some other factors directly affect the fruit-seedling separation effect (Zhu et al., 2013).

2 Materials and method

In this paper, processing tomato variety liger 87-5 was selected as test variety, and the tomato cultivation base of Tianshan Agricultural Development Co., Ltd. located in Hutubi County of Xinjiang Changji Hui Autonomous Prefecture was selected as test field. One hundred seedlings of tomatoes were randomly selected from the test site for organization of the biophysical data. The whole plant of liger 87-5 was among 0.79-8.3 kg, and the

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number of fruits per plant was between 21 and 122. Fruit weight was between 0.54 5.6 kg. Tomato fruit-seedling separation only deals with tomato vines which are harvested by a circular cutting machine (Qin, 2015). In the separation process, plant weight and number of fruits may affect the separation process, but the impact is not obvious. In the process of separation, it is necessary to consider the pericarp hardness of tomato fruit to optimize the design parameters of tomato fruit-seedling separation device (Liang, 2013). Since damage force of tomato fruit is an important index for tomato pericarp hardness, 200 tomatoes were randomly selected, and the fruit damage data are summarized in Table 1.

In the process of fruit-seedling separation, the effects of biomechanical factors were mainly taken into consideration.

The measurement items and instruments are:

(1) Vertical diameter, transverse: vernier caliper, the measuring range is 200 mm, the accuracy is 0.02 mm.

(2) Single fruit weight: electronic scale, the range is 5 kg, the accuracy is 1 g.

(3) Separation angle: angle ruler, the accuracy is 1 degree.

(4) Separation force: digital push pull HP-100, the range is 100N, the accuracy is 0.1N.

(5) Hardness: GY-4 digital hardness, the range is 1-50 kg, the accuracy is 0.5%.

The data of separation force are summarized in Table 2.

Table 1 Damage force data for tomato fruits

	Maximum value	Minimum value	Mean value (After removal of the maximum and the minimum values)
Transverse diameter, mm	52.6	27.3	43.3
Vertical diameter, mm	65	28.9	52.1
Single fruit weight, g	111	23	66.8
Transverse damage force, N	67.1	24.2	46.9
Vertical damage force, N	75.3	28.6	55.2

Table 2 Tomato fruit-seedling separation force

Mean value of transverse diameter, mm	Mean value of vertical diameter, mm	Mean value of fruit weight, g	Mean value of pericarp hardness, kg/cm^2	Angle, °	Separation force		
					Maximum value, N	Minimum value, N	Mean value, N
41.9	51.1	65.8	2.91	30	6.9	2.1	4.5
42.7	51.5	67.0	2.75	45	10.6	3.7	6.2
42.9	50.7	66.5	2.93	60	12.5	3.9	8.1
43.1	52.2	66.9	2.86	90	21.2	9.3	15.8

In measuring the data above, tomato vines were randomly selected from the test field to ensure the objectivity of the test. In measuring the damage force of tomato fruit, 200 tomatoes were divided into two groups for measuring transverse diameter and vertical diameter. The tomato fruits were placed on a steel plate of 10 mm in thickness, and they were pressed from above until they were broken; then the thrust on the gauge thrust was recorded in this process. One hundred sets of data were measured in each direction, the maximum and minimum values were removed and only the average was taken. In measuring the biological force in fruit-seedling separation, 40 tomato seedlings were randomly selected and divided into four groups of 10 seedlings. Then the biological force of the seedlings was measured at different angles respectively. In the test, 10 tomatoes with different shapes and different degrees of maturity were selected on the plant, and a total of 400 sets of data were obtained. In measuring biological force, first the fruit stems were pulled apart from an inclined angle, and the thrust on the force gauge was recorded; in measuring hardness, the tomato fruits were put on a steel plate of 10 mm in thickness, by holding the fruit by hand, the probe was inserted slowly into the fruit perpendicularly to the pericarp, and then the force on the hardness gauge was recorded.

3 Results and analysis

The double-power rotary and vibrating tomato fruit-seedling separation mechanism separates tomato fruit from seedlings through its inertial vibrating working parts. Soviet experts obtained the fourth status below in Figure 1 through analysis of the tomato fruit separation process with a high-speed photography (Tan, 2012):

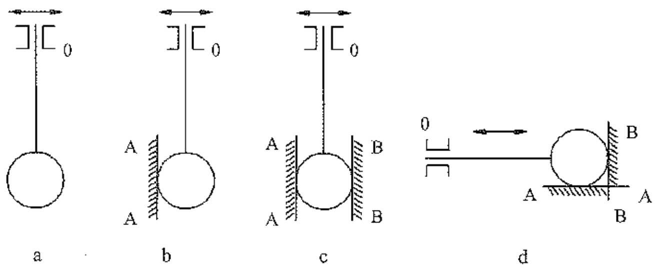

Figure 1 Four kinds of status in the process of fruit-seedling separation

3.1 Minimum impulse in fruit damage

Based on the analysis of the Soviet experts on the conveyor belt-vibrating sieve separation mechanism, in this paper, the roller-vibrating fruit-seedling separation mechanism was analyzed. First, the tomato seedlings with fruits were fed into the fruit-seedling separation device (Cao et al., 2009; Xiao, 2013). Assuming that the fruits collide with the vibration rod at an initial speed v_2, and the angle between its moving trajectory and coordinate axis was α; the vibration rod is in simple harmonic vibration at an initial speed of v_2, since the drum rotating speed is very low relative to vibration of the vibration rod, the rotating speed of the roller can be ignored; meanwhile, the slight movement relative to the coordinate system in theoretical analysis can also be ignored. The X axis was set to overlap with the center line through the fruit and vibrating rod, and the impact point is the coordinate origin O. When the fruits were fed into the separation mechanism, they collided with the vibrating rod, which was at maximum instantaneous speed. Under such circumstance, the collision could bring the greatest damage to the fruit. As the collision lasted for a very short period of time, it is assumed that the speed of the vibrating rod was not affected. When the fruit enters into the separation device, the vibration rod and tomato fruit collide, as is shown in Figure 2.

In such case, it is assumed that the positive pressure N was the same with the OX axis. Thus, the projection change of fruit velocity on this axis is the same as that of the collision of two semi-elastic objects along a straight line, namely:

$$u_{2x}=e(v_1-v_{2x})+v_1 \quad (1)$$

where, e is coefficient of restitution; u_{2x} is the projection of fruit velocity on X axis after collision, m/s; v_1 is the speed of a vibrating rod, m/s; v_{2x} is the projection of fruit velocity on X axis before collision, m/s.

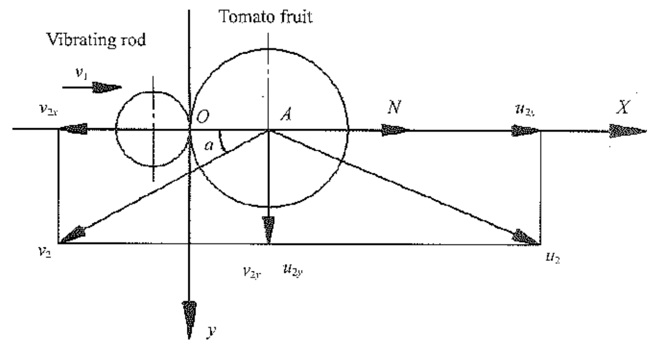

Figure 2 Collision between tomato fruits and the vibration rod

The velocity of Y axis is:

$$u_{2y}=v_{2y}=v_2\sin\alpha \quad (2)$$

where, u_{2y} is the projection of fruit velocity on Y axis after collision, m/s; v_{2y} is the projection of fruit velocity on Y axis before collision, m/s; α is the angle between v_2 and X axis, rad.

The impulse on fruit at this time is:

$$I=m(u_{2x}-v_{2x})=m(1+e)(v_1+v_2\cos\alpha) \quad (3)$$

At this time, there are two kinds of possibilities for tomato breakage: first, the fruit might have been broken by the large impulse from the vibration rod; second, the fruits were crashed by the accelerated falling of the vibration rod, when the impulse is less than the direct blow to the fruit, so the impulse I_m by the vibration rod is the limiting value, namely the coefficient of restitution remains unchanged within the limiting value of impulse.

$$I_m=m(1+e)v_m=m(1+e)\sqrt{2gH_m} \quad (4)$$

where, H_m is the falling height of the fruit to the support surface, m. The fruit may be broken if the height is increased.

According to tests and experiments in mechanical harvesting, liger 87-5 with $H_m\geq1000$ mm may easily get damaged by the vibration separation device of tomato harvesters, when vibration $H = 650$ mm in working. The most unfavorable condition for tomato fruit damage is the maximum speed of vibration rod in collision of fruit and the rod, namely, $v_1=A\omega$, angle $\alpha=0$, $v_1=v_2$, and:

$$v_1\leq\sqrt{0.5gH_m} \quad (5)$$

Put H_m=650 m into the Equation (5) and get

$v_1 \le \sqrt{0.5\times 9.8\times 0.65} = 1.78$ m/s.

Then put the maximum height H_m=1000 into the Equation (5) and get $v_1 \le \sqrt{0.5\times 9.8\times 1} = 2.21$ m/s

When A=0.05 m, the minimum angular frequency of vibration of the fruit separation device should be: $\omega_{\min} \le \frac{v_1}{A} = \frac{1.78}{0.05} = 35.6$ s^{-1}

The maximum angular frequency is: $\omega_{\max} \le \frac{2.21}{0.05} = 44.2$ s^{-1}

The minimum impulse for fruit damage obtained by the analysis above was 18.5 N·s. Such case of collision between the tomato fruit and the vibration rod was rare in the process of fruit-seedling separation. It was found that this was the main reason for fruit damage.

3.2 Minimum impulse in fruit-seedling separation

In the process of fruit-seedling separation, the separation force was the smallest when the fruit was in a free suspension status (Hao, 2015). At this time, the minimum impulse was provided by the fruit-seedling separation device. The analysis of tomato fruit separation process is shown in Figure 3.

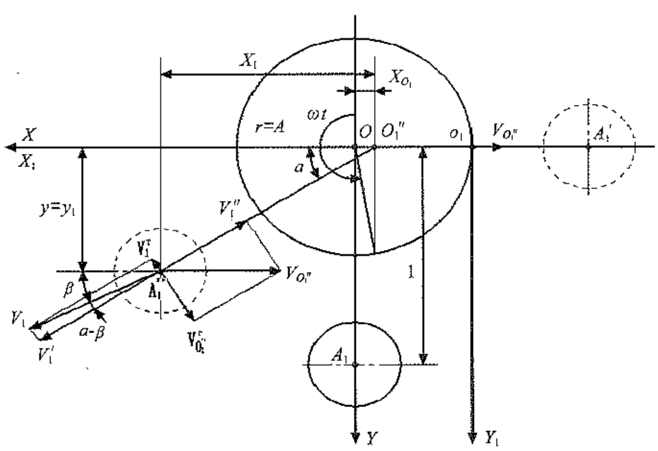

Figure 3 Modeling diagram of tomato fruit-seedling separation process

A fixed coordinate system XOY and transport motion coordinate system $X_1O_1Y_1$ were set. Set O_1 as the pendulum suspension point, and let O_1 represent the motion rule of the working surface, and get:

$$x_{o1} = A\sin\omega t \tag{6}$$

where, A is amplitude of oscillation, mm.

The equation of fruit gravity center is:

$$x = x_{o1} + x_1 \tag{7}$$

$$y = y_{o1} + y_1 \tag{7}$$

where, x_1 and y_1 are the coordinates of fruit gravity in the transport motion coordinate system. In an assumed case, y_{o1}=0, namely $y = y_1$.

When the pendulum vibration starting point deviates from the vertical angle $\varphi \ge 90°$, namely, it is in the horizontal position, then the velocity of the suspension point is:

$$\dot{x}_{o1} = A\omega\cos\omega t \tag{9}$$

The impulse at time of collision is:

$$I = m(v_1'' - v_1') \tag{10}$$

where, m is fruit weight, kg.

v_1' is the projection of fruit velocity on pendulum suspension line at the instant before collision, m/s;

v_1'' is the projection of suspension point on pendulum suspension line, m/s; Figure 3 shows that:

$$v_1' = v_1\cos(\alpha - \beta) \tag{11}$$

where, v_1 is the fruit velocity at the instant before collision, m/s; β is the angle between velocity vector v_1 and OX.

The modulus of velocity is:

$$v_1 = \sqrt{x^2 + y^2} = \sqrt{(A\omega)^2 + (gt_1)^2} \tag{12}$$

The direction of velocity vector was determined as:

$$\beta = arctg(\frac{dy}{dx}) = arctg(\frac{gt_1}{A\omega}) \tag{13}$$

And get:

$$v_1' = \sqrt{(A\omega)^2 + (gt_1)^2}\cdot cos\{arctg[\frac{gt_1^2}{2(A\omega t_1 - 1 - A\sin\omega t_1)}] - arctg(\frac{gt_1}{A\omega})\} \tag{14}$$

Suppose that the connection of the suspension points is inelastic, the final velocity of the fruit is:

$$v_1'' = \dot{x}_{o1}\cos\alpha = A\omega\cos\omega t_1\cos[arctg(\frac{gt_1}{2(A\omega t_1 - 1 - A\sin\omega t_1)})] \tag{15}$$

Due to the short time of impulse occurrence, then suppose that the value and direction of the speed vectors v_1' and v_1'' in collision stay unchanged, then:

$$I = m[A\omega\cos\omega t_1\cos A' - \sqrt{(A\omega)^2 - (gt_1)^2}\cos(A' - B')] \tag{16}$$

where, $A' = arctg[\frac{gt_1^2}{2(A\omega t_1 - 1 - A\sin\omega t_1)}]$,

$B' = arctg(\frac{gt_1}{A\omega})$.

When the initial position φ>90°, namely, when the pendulum was in horizontal status, collisions may occur. At this time the minimum value of the impulse is:

$$I_{\min}=2mA\omega \tag{17}$$

The results show that when the $A\omega$ = 1.78 m/s, A = 0.05 m, l = 0.05-0.1 m, and the fruit weight G = 0.066 kg, the minimum separation impulse is 2.3 N·s.

At this time, the tomato fruits were in free suspension, which is the best status for tomato fruit-seedling separation. In the process of tomato fruit-seedling separation, normally, the tomato fruits are connected with the stems; there are few cases of free suspension; also there are few cases of firm grasp by the stem. In the test study, the status of tomato fruit is changing, due to the high frame of stem and leaf layer, the fruit position changes in the vibration process, and results in the situation stated above. Related test studies showed that the most appropriate feeding amount of tomato fruit is dependent on the variety, plant growth, the number of leaves, the biological force of fruit connection, and other factors.

2.2 Field test verification

In order to verify the theoretical conclusions of section 3, an experiment was carried out in Tianshan Agricultural Development Co., Ltd. located in Hutubi County of Xinjiang Changji Hui Autonomous Prefecture. According to the "Operating quality for tomato harvesters" (NYT 1824-2009), the no-load test was made after the prototype was installed, and test results and analysis results were contrast. Based on test results, the initial design parameters were adjust. The test table is shown in Figure 4.

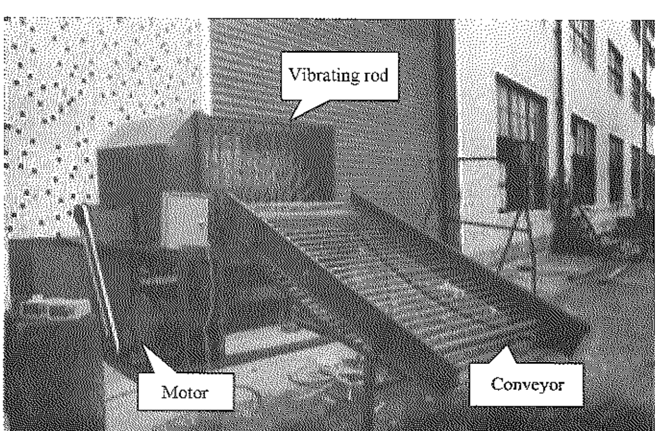

Figure 4 Test table of fruit-seedling separation

The experiments show that the separation rate of the separation device is more than 97%, and the breakage rate is less than 4%. The results show that the separation mechanism designed according to the theoretical model has good separation effect.

4 Conclusions

In this paper, the biophysical and mechanical properties of tomato seedlings were collected and analyzed by tests and modeling. The following results were obtained by the test: the average pericarp hardness of liger 87-5 was 286 kg/cm^2; the mean transverse damage force of fruit was 46.9 N, the mean value of vertical damage was 55.2 N, and the maximum biological force in separation was 15.8 N at 90°. The process of fruit-seedling separation of tomato fruits in vibration was analyzed theoretically, and the minimum impulse value of 18.5 N·s for damage, and the minimum impulse value of 2.3 N·s for separation were obtained. The results may provide the theoretical basis for the design and manufacturing of the fruit-seedling separation device in the future.

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