STUDY ON THE CHARACTERISTICS OF *Cerasus humilis* FREE FALLING IMPACT
/
钙果自由落体冲击平板特性研究

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ABSTRACT
The contact parameters between calcium fruit and comb teeth are the key to the virtual picking test. In this paper, the physical test of free-falling impacting plate on the self-built test bench and the centre rotation composite simulation test of rigid body dynamics were carried out. The relationship between the contact parameters and dynamic characteristics was obtained, and the contact model was optimized. The contact stiffness k=0.868, force index e=1.91 and damping C=5.56E-4 were obtained when the height of the free falling body was 500 mm. The model was applied to lower free-fall simulation test, and the obtained results were in good agreement with the physical test results. The contact model can be used in the subsequent picking simulation.

摘要
钙果与梳齿之间的接触参数是进行虚拟采摘试验的关键，本文通过自建试验台进行了自由落体冲击刚性板的物理试验与刚体动力学的中心旋转复合仿真试验。获得了接触参数与动态特征之间的关系，并通过优化得到了接触模型，自由落体高度 500 mm 时获得的接触刚度 k=0.868，力指数 e=1.91，阻尼 C=5.56E-4。并将模型应用到更低自由落体高度仿真试验中,得到的结果与物理试验结果一致性很高，该接触模型可以用于后续的采摘仿真。

INTRODUCTION
When *Cerasus humilis* is harvested, the comb teeth are used to comb it off by impact, the fruit gets kinetic energy from the comb teeth, and there is a tendency to splash away from the picking mechanism *(Liu et al., 2021)*. So, it is necessary to study the dynamic phenomenon of the fruit after impact. Physical test method and virtual test method are commonly used to study dynamic behaviour of fruits. Since the fruits on the branches are often very close *(He et al., 2018)*, the behaviour of combing is a group behaviour. The physical test method is difficult to record the trajectory and other parameters of each fruit, which cannot be studied in detail. However, virtual experiments can obtain a lot of information about each element, such as displacement, velocity, collision force, energy, etc. As a biomaterial, *Cerasus humilis* has complex mechanical properties, and collision is the main force form in the harvest process. In order to study the dynamic behaviour of fruit after being impacted, it is necessary to obtain the contact parameters of the interaction between comb teeth and fruits. The free-fall impact test is the closest method to the picking. This method has been widely used by previous researchers to study the impact damage sensitivity of fruits such as apples, pears and peaches *(Yu et al., 2014; De et al., 2015; Gancarz et al., 2016; Komarnicki et al., 2017; Surdilovic et al., 2018)*. Of course, the free-fall impact test also has defects, the impact point of the fruit and the direction of rebound can't be determined. *Lewis et al* similarly concluded that the drop test technique was the most realistic simulation of what actually happened, although it was difficult to control the point of impact *(Lewis et al., 2007)*.

It is generally believed that the deformation rate significantly affects the mechanical properties of fruits, so it has become a problem to be solved in engineering applications to study the mechanical properties of fruits under different impact velocities and establish corresponding dynamic mechanical models. The impact test of a single fruit is a good compromise between applying actual load and method with sufficient control parameters, which is repeatable and controllable, and is an important way to obtain the contact parameters of the fruit and comb *(Brusewitz et al., 1994)*.

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In view of the advantages and disadvantages of the above physical tests and virtual tests, this study made a comparative analysis of the physical tests and virtual tests to reproduce the mechanical phenomena of the fruit in the virtual tests. In this process, the simulation parameters are constantly adjusted to achieve the above purpose, and the accurate contact parameters between the fruit and the plate are finally obtained.

MATERIALS AND METHODS

Physical test of plate impacted by free falling fruit

The material was "Nongda No. 4" *Cerasus humilis*, which was sampled one day later than the quasi-static test in the literature (*Shilei et al., 2023)*. The samples were taken from the same field and the same sample screening and processing methods were used, which can be regarded as a same batch.

This experiment adopts a self-made test bench, which is composed of force sensor, plate, signal acquisition card, transmitter, processing software, etc. The structure and simplified model are shown in Fig.1. The cylindrical pressure sensor (AR-DN331) is selected, the accuracy is 0.1% full scale, the response frequency is 15 kHz. According to the weight of the fruit and the height of the test, the approximate range of the impact force is preliminarily calculated by the momentum theorem, and the range is selected as 50 N. Transmitter can output 0 V to 5 V voltage signals. The signal acquisition card converts an analogue signal into a digital signal. The USB3200N 12-bit acquisition card is selected, and the sampling frequency is as high as 5 MHz. The response frequency of sensor and acquisition card is considered comprehensively, and the sampling frequency is set to 10 kHz. Software is installed in computer, which can display and record in real time. One end of the sensor is reliably connected to the plate, the other end is fixed to the table. The plate is made of steel with a diameter of 100 mm and a thickness of 3 mm. The column with a steel ruler on the surface is fixed on the table, and the tray is adsorbed on the surface of the steel ruler with a magnet, and its centre is facing the plate.

Fig. 1 - Free fall impact test device and the simplified model

1. Transmitter; 2. DC power supply; 3. Signal acquisition card; 4. Plate and force sensor; 5. Column; 6. Tray; 7. Software

The test device can obtain the time history data of the impact force. The force acting on the contact surface acts as a function of time depending on the mass of the fruit, the height it falls, and the contact radius of the fruit. The contact force acting as a function of time $F(t)$ can be easily obtained by computer-controlled data acquisition systems, and the method based solely on $F(t)$ would be highly desirable (*Meredith et al., 1990)*.

In the actual *Cerasus humilis* picking, the fruit is accelerated after comb, or can fall outside the comb tooth surface, then the impact speed should be limited to a certain range. When the fruit is in free fall, even if the height is only 500 mm, regardless of air resistance, its impact speed will reach 3.16 m/s, according to the previous picking experience with simple comb teeth, the collision at this speed is enough to make the fruit splash. In order to investigate the dynamic behaviour of fruits at different impact speeds, physical impact tests were carried out at the height of 100 mm, 200 mm, 300 mm, 400 mm and 500 mm, respectively.

When the fruit falls freely, its posture will be automatically adjusted, and the minimum cross-section will be perpendicular to the direction of gravity, so the cheek of the fruit will first contact with the target surface, which is why it was found in previous impact test studies that this part was the most severely damaged (*He et al., 2019)*. However, it is not certain when the height is low. Therefore, before the fruit falls, the cheek is turned down in advance, so that the first contact is made to that part.

Due to the uneven distribution of the external shape and internal mass of the fruit, the direction of fruit after the first contact with the plate is uncertain. Therefore, the point and angle of the second contact are not controllable, and it is likely to pop out of the range of the plate without obtaining complete data.

In the study, the samples with the first two impact points on the plate are considered to be valid, and at least 5 valid sample data are obtained for each height.

In any impact test device, the fruit does not impact directly on the sensor, but on the plate that is firmly connected to the sensor, and this is no exception. So, the signal received by the sensor is not only the impact force. It includes two parts: the gravity of the plate and the impact force of the fruit on it. The output signal of the sensor is a standard voltage signal with a range of 50 N and a signal amplitude of 5 V, then each voltage signal corresponds to a force value of 10 N, and the impact force value is calculated by formula (1):

$$F = (V_1 - V_0) \times 10 \tag{1}$$

where: V_1 - the measured voltage value, V_0 - static voltage signal value

The typical impact curve obtained from the impact test is shown in Fig.2, the drop height of which is 500 mm, these curves are obtained by subtracting the gravity portion of the plate. Three distinct impacts usually can be found in the data obtained from each sample, and the impact force gradually decreases. The first peak value of each curve is the fruit impact force value, and the three impact forces in the figure are 9.47 N, 4.22 N and 2.62 N respectively. When an increase in voltage is detected that exceeds the noise level of the force sensor, contact is initiated. There were difficulties in identifying the origin of the impact (*McGlone et al., 1997)*. When the value returns to the noise level of the sensor, it does not indicate that the fruit has separated from the plate, but that the vibration of the plate above the sensor has stopped.

The first peek is caused by the impact force in any curve. Since strain is the basis of force measurement, so when the fruit bounces off the plate, the plate will obtain a certain kinetic energy, damped free vibration occurs, then the strain material of the sensor has stiffness and damping. Previous researchers have described plates as being infinite mass and stiffness. In fact, no matter what form of sensor is used, there will be strain, there are plates between the force measuring element and the impact object, and the plate in order to ensure the reliability of the impact, generally relatively large, its weight can't be ignored. Some researchers have adopted a structure similar to this without considering this problem (*Lu et al., 2007)*. This is a problem introduced by the test device, the mechanical properties of the device will affect the response of the fruit collision, and must be considered.

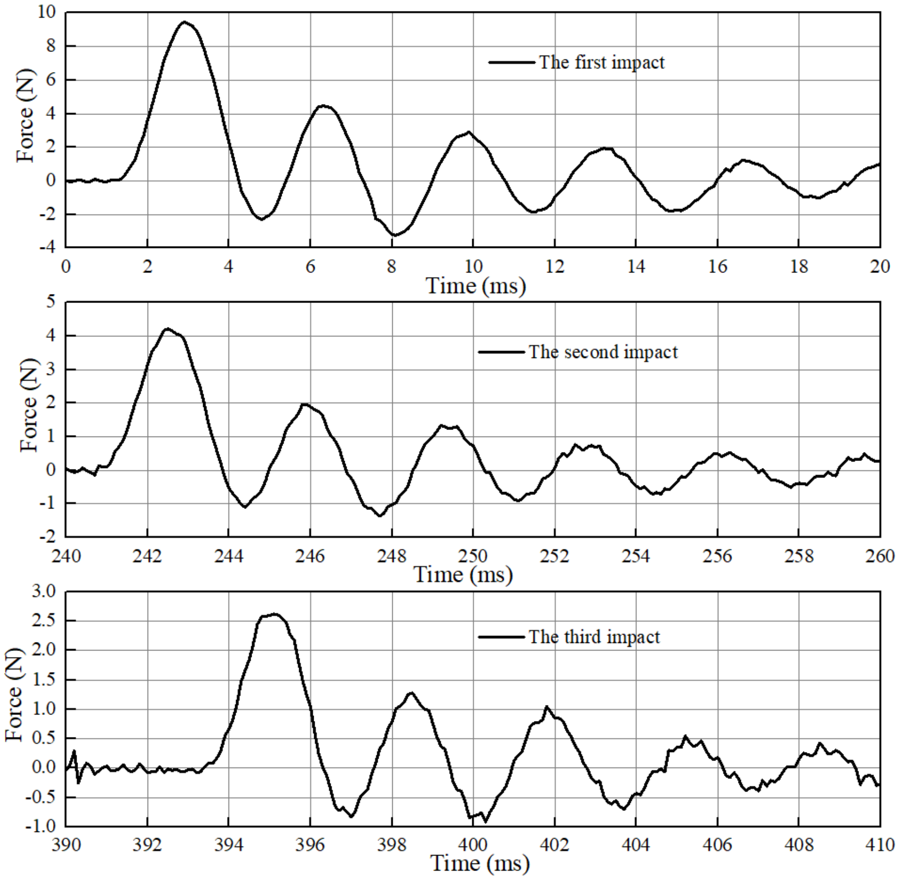

Fig. 2 - Typical impact force time history curve

Test the vibration characteristics of the device

Before studying the fruit impact test device, it must first be understood the vibration characteristics of the test device itself. Their height by the fall, each shock vibration between the peaks of vibration period statistics for T_d=3.5±0.1 ms. The second and third peaks of each shock are caused by the vibration of the test system itself. The smaller the impact force is, the greater the noise interference of the signal, the second and third peaks of the first impact are selected, and the attenuation coefficient is calculated to solve the damping ratio of the system, see formulas (2) and (3).

In theory, the ratio between the peaks of displacement is used to represent the degree of attenuation, but what is obtained in the test is the impact force. Under constant stiffness, the displacement is proportional to the impact force, so the impact force ratio is used here to calculate the attenuation rate.

- logarithmic decrement: $$\delta = \ln\frac{A_3}{A_2} = \frac{2\pi\xi}{\sqrt{1-\xi^2}} \quad (2)$$
- damping ratio: $$\xi = \sqrt{\frac{\delta^2}{\delta^2+4\pi^2}} \quad (3)$$

where: A_2, A_3 - the second and third peak forces formed by the first impact.

The average value and standard deviation of the damping ratio at each height of free falling body are shown in Table 1, and it can be found that they are very close. The accuracy of the test results and the stability of the device are confirmed. The overall average damping ratio is 0.073±0.008.

Table 1

The average and standard deviation of damping ratio respectively

Height of free fall（mm）	100	200	300	400	500	Overall average
Average damping ratio	0.069	0.074	0.075	0.076	0.068	0.073
Standard deviation	0.013	0.007	0.006	0.003	0.011	0.008

The vibration circular frequency of the test system is: $$p_d = \frac{2\pi}{T_d} = 1797 \quad (4)$$

where p_d represents natural frequency of the damped system, which intrinsic dimension is 1, unit is 1.

T_d *is* the time between peaks, value is 3.5 ms in the text, which is obtained by test statistics

Then the stiffness of the test system is: $$k = p_d^2 * m = 645842\ N/m = 645.8\ N/mm \quad (5)$$

Where k is the system stiffness, N/mm, m is the mass of plate, 0.2 kg.

Damping: $$c = \xi * 2\sqrt{mk} = \xi * 2\sqrt{0.2 * 645842}$$
$$= 0.073 * 721 = 52.47\ N \cdot s/m = 0.05247\ N \cdot s/mm \quad (6)$$

where c is the system damping.

Dynamic impact simulation of fruit

ADAMS is suitable for solving macroscopic mechanical dynamics problems. The collision and movement trajectory of *Cerasus humilis* in picking is a typical dynamic problem, so it is carried out in this platform. The contact parameters between fruit and comb are the key of virtual simulation. Therefore, the above physical experiments of fruit free-falling impacting plates are carried out. However, only physical tests have not been able to determine contact parameters. Perhaps this simple impact model can be calculated through theory, but our purpose is to study the picking process in the later stage, when the theoretical calculation will not be completed, so numerical simulation is adopted to find the contact parameters. Contact parameters such as contact stiffness and damping were calibrated in combination with physical experiments and numerical simulations *(Coetzee et al., 2016; 2017)*.

Preliminary calculation of contact parameters

Hertzian contact is the most commonly used contact theory. Its application has some basic assumptions, such as smooth and homogeneous contact objects, small elastic deformation, and only normal pressure on the contact surface. In fact, the impact test of the fruit has gone completely beyond the scope of the assumptions. However, the contact stiffness obtained by this theory is still valuable for reference, and can be used as a starting point for optimizing the search for equivalent contact parameters.

According to Hertz contact theory, the relevant formula is as follows (7, 8, 9, 10):

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2} \tag{7}$$

$$\frac{1}{E^*}=\frac{1-v^2}{E_1}+\frac{1-v^2}{E_2} \tag{8}$$

$$\mathrm{a}=\left(\frac{3PR}{4E^*}\right)^{1/3} \tag{9}$$

$$\delta=\frac{a^2}{R}=\left(\frac{9P^2}{16RE^{*2}}\right)^{1/3} \tag{10}$$

where: a - contact radius; δ - contact depth; P - contact force at collision.

R_1 is defined as the fruit radius, with an average of 10 mm. R_2 is the radius of the plate, which is infinite. the equivalent radius R is calculated by formula (7) to be approximately equal to R_1 is 10 mm.

E_1 is defined as the elastic modulus of the fruit. Since the core is in the middle of the fruit and thicker pulp is separated from the plate during impact, the stiffness of the pulp is considered to be similar to that of the fruit. Therefore, E_1 is preliminarily set 1 MPa (*Shilei et al., 2023*), and E_2 is the elastic modulus of the plate, which is very large compared with the fruit, so the equivalent elastic modulus is shown in formula (11).

$$E^*=E_1/\left(1-v_1{}^2\right)=1.28\,MPa=1.28\,N/mm^2 \tag{11}$$

According to the above formula (7, 8, 9, 10), the collision force calculation formula (12) can be obtained:

$$P=\left[\left(\frac{16RE^{*2}}{9}\right)^{1/2}\right]\delta^e \tag{12}$$

contact stiffness $$k=\sqrt{\frac{16RE^2}{9}}=5.4\,N/mm$$

The prediction of contact dynamic behaviour largely depends on the choice of contact force model. The definition of contact generally includes two algorithms, namely collision function method and penalty function method. The most commonly used collision function method is actually implemented using the 'impact' function in the Adams solver.

The contact force is calculated as shown in formula (13).

$$F_{impact}=\begin{cases}0 & q\geq q_0\\ k(q_0-q)-C\frac{dq}{dt}\cdot step\left(q,q_{0,}-\delta,1,q_0,0\right) & q\leq q_0\end{cases} \tag{13}$$

where q_0 - initial distance; q- actual distance; dq/dt - distance rate; k corresponds to the contact stiffness; e stands for resilience index; δ is the penetration depth; C is damping.

Modelling in ADAMS

The geometric model of the fruit and plate are built in SolidWorks, which is better at building complex 3D models, and then import it into ADAMS *(Du et al., 2021)*. Set the weight of the fruit to 4.8 g, and adjust the height of the lower edge of the fruit to the test height. A spring is used to connect the plate to the earth, and an axial moving pair is set. The stiffness is set to 645.8 N/mm, and the damping is set to 0.05247 N.s/mm.

In order to reduce the number of contact parameters to be optimized, the effects of penetration depth on the contact force and the time between the first two collisions are first investigated. The contact parameters are set according to the above calculation, k is 5.4, e is initially set as 2, and C is 0.1% of k (5.4E-3). Simulation results show that the rebound height is much lower than the physical test, indicating that the model parameters are seriously deviated. If the rebound height is low, the energy loss is large, which has the greatest relationship with damping. If the damping is too large and too much energy is consumed, the damping is reduced, and the initial setting is 4E-4. The penetration depth is set to 0.1 mm, 0.01 mm and 0.001 mm respectively. Part of the results are shown in Table 2. The analysis shows that the coefficient of variation of the first impact contact force and the interval time between the first two impacts is small, and these indicators tend to be stable with the decrease of penetration depth. The penetration depth can be set to a smaller value of 0.001 mm to ensure that damping is involved in the calculation as early as possible.

Table 2

Impact forces and impact intervals at different penetration depths

Penetration depth（mm）	First impact force（N）	Interval between first two impacts（ms）
0.1	27	335
0.01	26.2	314
0.001	26.2	314
Average	26.5	321
Standard deviation	0.38	9.8
Variable coefficient	1.42%	3.06%

Orthogonal rotating centre composite virtual test

If the above Settings are used, the simulated first impact contact force will be much larger than the value of the physical test for comparison, regardless of the adjustment of other parameters. Because k is the factor that has the greatest influence on the contact force, its value is reduced, and the initial value range is 0.3 to 1 N/mm. In the selection principle of e, when k is low, the value is large, ranging from 1.5 to 3. If C takes the value of 4E-4 in the above test, its value range is appropriately expanded to 1E-4～6E-4.

A Central Composite Experiment Design (CCD) is done through Design Expert 8.0.6, and through the response surface optimization to find the optimal parameter combination. The contact parameters of each design point are input into the simulation model, and the corresponding target data is calculated, as shown in Table 3.

Table 3

Three-factor CCD experiment design

Run	Stiffness(A)	Force index(B)	Damping(C)	Force（N）	Interval（ms）
1	1	2.25	3.5E-4	14.9	334
2	0.44	1.8	2E-4	9.4	380
3	0.65	2.25	6E-4	11.8	275
4	0.86	1.8	5E-4	11.2	310
5	0.44	2.7	5E-4	13.6	282
6	0.65	2.25	1E-4	13.6	385
7	0.44	1.8	5E-4	7.6	276
8	0.3	2.25	3.5E-4	9.7	328
9	0.86	2.7	2E-4	18.3	334
10	0.86	2.7	5E-4	15.1	287
11	0.65	2.25	3.5E-4	13.1	326
12	0.44	2.7	2E-4	14.3	362
13	0.65	1.5	3.5E-4	8.4	323
14	0.65	3	3.5E-4	17.7	301
15	0.86	1.8	2E-4	12.4	372

RESULTS

Analysis of variance

The first contact force represents the maximum contact strength. The variance analysis of the contact force data is shown in Table 4. The model is extremely significant, with a coefficient of determination (CoD) R^2 of 0.978, is shown in formula 14, indicating a high correlation between the model and the experimental factors. The factor A, B and C all have extremely significant influence on the model. It can also be seen from the influence of all factors on the contact force in Fig.3 that the contact force varies greatly within the variation range of all factors.

Table 4

Variance analysis of the first contact force

Source	DF	SS	F-value	P-value	Sig
Model	3	135.74	160.46	<0.0001	**
A	1	31.82	112.84	<0.0001	**
B	1	96.70	342.95	<0.0001	**
C	1	7.22	25.59	0.0004	**
Residual	11	3.1			
Total	14	138.84			

*Notes: SS is the sum of squares, DF is degrees of freedom, Sig is significance, ** means P < 0.01, $F_{0.01}(1,11)=9.65$, $F_{0.01}(3,11)=6.22$.*

$$F_{max-1} = -3.79 + 7.33A + 5.97B - 4890C \tag{14}$$

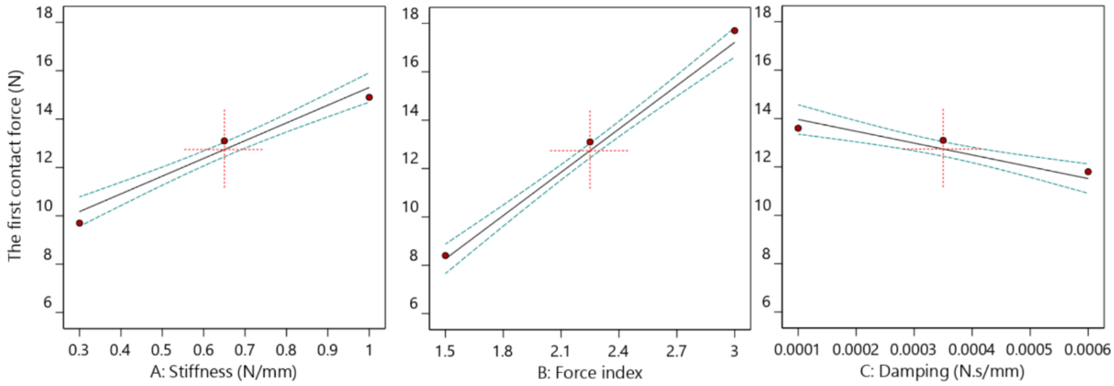

Fig. 3 - Single-factor relationship between first contact force and contact parameters

The interval between two contacts represents energy absorption. The variance analysis of the interval time data is obtained in Table 5. The model is extremely significant, and the CoD R^2 is 0.994, is shown in formula 15, indicating a high correlation between the model and the factors. The stiffness k is not significant to the model, e and C are extremely significant to the model, and the interaction terms AB, AC, BC and B^2 are extremely significant. It can also be seen from the influence of various factors on the contact force in Fig.4 that the contact force varies greatly within the variation range of B and C.

Table 5

Analysis of variance between two contact intervals

Source	DF	SS	F-value	P-value	Sig
Model	9	2750.33	158.17	<0.0001	**
A	1	12.55	0.7216	0.4237	
B	1	885.99	50.95	0.0002	**
C	1	16730.16	962.13	<0.0001	**
AB	1	300.12	17.26	0.0043	**
AC	1	703.13	40.44	0.0004	**
BC	1	190.13	10.93	0.0130	**
B^2	1	430.21	24.74	0.0016	**
Residual	7	17.39			
Total	14	138.84			

Notes: ** means P < 0.01, $F_{0.01}(1,7)=12.2$, $F_{0.01}(1,7)=6.72$.

$$t = 325.69 + 47.03B - 5.98 * 10^5 C - 66AB + 3.03 * 10^5 AC + 73539BC - 30.67B^2 \tag{15}$$

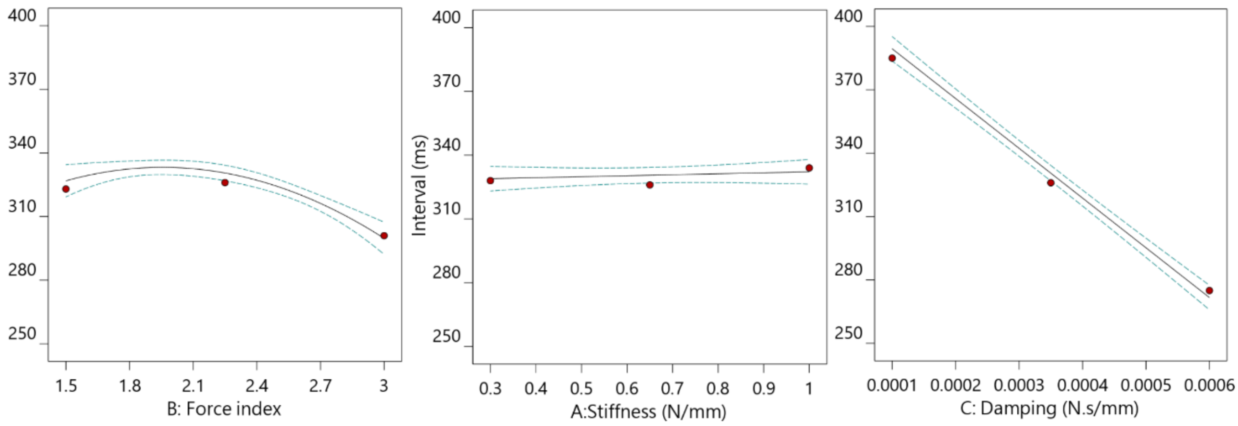

Fig. 4 - Single-factor relationship between two contact intervals and contact parameters

Contact model optimization

The sample data closest to the average value of 500 mm free-fall impact is taken as the optimization target. The first impact force of this sample is 11.3 N, the interval time of the first two impacts is 299 ms, and the appropriate error range is set. If the two results data of the above sample can be reproduced in ADAMS, The contact parameters are reasonable. The optimized parameters are k=0.868, e=1.91, C=5.56E-4.

This set of data is used to construct a contact model, and the corresponding collision results data is calculated and shown in Table 6 together with the physical test data. A difference of up to 2% can been seen.

Through experimental design and optimization, the optimal contact parameters are found accurately, and the physical test phenomenon reappear well in the simulation test. Previous studies have also verified the feasibility of finding contact parameters through optimization through standard rubber balls *(Tabatabaekoloor et al., 2013)*.

Table 6

Comparison of contact force and interval at free fall of 500 mm

	Force（N）	Interval（ms）
Physical test	11.3	299
Virtual test	11.4	293
Difference	0.1	6
Difference/Physical test	0.9%	2%

The contact parameters obtained above are input into the collision models of other free-falling bodies for simulation. The corresponding contact collision data are obtained. Compared with the sample data under the height of the falling body, the difference between the physical and simulation test results is only 7% at most. Due to space limitations, the data are not listed here. Therefore, the above contact model can be used to simulate the impact below the velocity corresponding to the height of the free-falling body.

CONCLUSIONS

(1) By analysing the time history data of the impact force, it is found that the impact force of each collision presents the phenomenon of damped free vibration attenuation, and the connection between the fruit plate and the earth is not rigid. Then, the vibration parameters are obtained by theoretical calculation.

(2) The influence of each contact parameter on the contact force and interval was obtained through a set of orthogonal rotating centre composite tests. The optimal contact model was obtained by using the optimization method by comparing with the physical test. The contact stiffness k=0.868, force index e=1.91 and damping C=5.56E-4 are obtained when the height of the free falling body is 500 mm. The model is applied to lower free-fall simulation test, and the obtained results are in good agreement with the physical test results. The contact model can be used in the subsequent picking simulation.

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