High-speed camera-based coefficient of restitution of apple under three-dimensional fruit-to-fruit collision in air for vibration harvesting

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Abstract: The coefficient of restitution (CoR) is an important parameter for designing vibration-harvesting machinery. There are three main types of fruit-to-fruit collisions during vibration harvesting: collision between fruits collected using a collection device and falling fruits, collision between fruits on branches before being removed, and collision of fruits in the air. The CoR for the first two types of collision was investigated separately using drop and pendulum methods. However, there have been few studies on CoR for the collision of fruits in the air. In this study, a platform was designed to simulate the collision of fruits in the air during vibration harvesting for the 'Gala' apple, where influences of collision velocity on CoR were studied. Images from a high-speed camera were processed based on RGB to Lab conversion to extract the bruise surface and calculate the bruise volume. Total bruise volume, the sum of two apple bruise volumes, was calculated and analyzed in relation to the CoR. Results showed that the CoR decreased with collision velocity increasing from 1.0 m/s to 1.4 m/s, where the CoR reached 0.93 or higher when collision velocity was 1.0 m/s, making fruits not bruise, while fruits began to bruise when collision velocity increased from 1.2 m/s. The CoR did not continue to decrease when collision velocity exceeded 1.4 m/s due to rotation. There was little correlation between total bruise volume and the CoR due to the composite motion of fruits in the air, indicating that the CoR may not be an indicator to determine the degree of fruit bruise when the fruit made a composite motion during the collision. Therefore, this research is expected to guide the establishment of a more accurate fruit model to design optimal vibration harvesting machinery.

Keywords: coefficient of restitution, three-dimensional displacements, fruit damage, image analysis, rotational motion
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1 Introduction

Vibration harvesting, a common method for tree-grown fruit mechanical harvesting, mainly relies on numerical techniques to optimize device design. Apple, a high-yield fruit crop, could be efficiently harvested through vibration harvesting[1-3]. The principle is to transfer kinetic energy to branches, generating separation forces at fruit stalks to separate fruits from a tree[4]. Different excitation frequencies and amplitudes cause various tree branch responses, allowing fruit removal through pendulum, tilt, or rotation motions during vibration[5]. There are cases when fruits collide with each other in the air after being removed and damaged. Optimization of parameters like operating frequency, vibration amplitude, and clamping position helps to reduce fruit damage and enhance harvesting efficiency[6,7]. Finite element method (FEM) application for contact modeling allows prognosis of material

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behavior under load and design equipment. Zhou et al.[8] used FEM and experiments to analyze dynamic responses of the jujube fruit-stem system, predicting fruit shedding movements. Therefore, simulation models can be used to analyze the dynamic response of the apple harvesting process and optimize equipment design.

The coefficient of restitution (CoR) can be used to analyze the kinematics and collision physics of various materials in collision simulation models and experiments. It serves as an input for damping parameters in viscoelastic contact models to describe energy retention or loss during collisions[9,10]. There are few CoR-related studies on biological materials such as grains, vegetables, and fruits due to their irregular shape. For apples, collision velocity (the kinetic energy transferred to fruits during vibration harvesting) could influence CoR to reduce damage. Since CoR could imply the degree of damage sustained during a collision, when CoR is below a certain threshold, fruits are less likely to be damaged. Conversely, if CoR is too high, fruits may bounce off with greater force, potentially causing damage, due to less kinetic energy being dissipated during the collision and more being used for the rebound. The discrete element model (DEM) also used CoR to predict fruit damage. Thus, CoR is crucial in collision simulation models for fruit.

During vibration harvesting, there are three main types of fruit-to-fruit collisions: between fruits on a collection device and falling fruits, between fruits on branches before removal, and in the air after removal and before reaching the collection device. Most studies focus on the pendulum and drop methods to derive the correlation between CoR and fruit damage. The pendulum method simulates collisions between fruits on branches, while the drop method models collisions between collected and falling fruits[11]. However, these methods do not account for the collision of fruits in the air, which could also have implications for fruit quality and overall harvesting efficiency. Since fruit damage affects consumer acceptance and limits vibration harvesting's application in the fresh fruit market[12-15], understanding all collision types is crucial. Hence, it is necessary to simulate the collision of fruits in the air during vibration harvesting.

The main objectives of this study were: 1) to realize the collision of fruits in the air; 2) to explore the effect of collision velocity on CoR; 3) to analyze the relationship between the CoR and fruit damage.

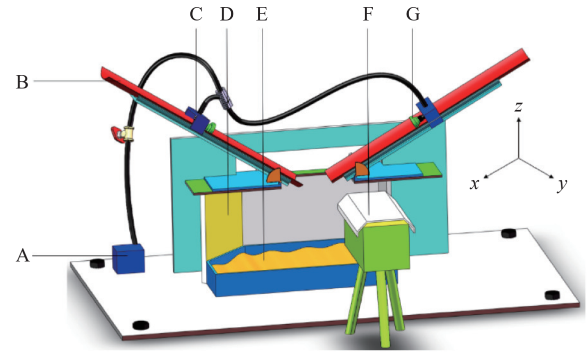
2 Materials and methods

2.1 Material and sample preparation

This study was carried out on the 'Gala' apple, a common apple cultivar in local markets. Ready-to-harvest apples were hand-picked randomly from an apple orchard in Fufeng, Shaanxi, China (latitude: 34°22′21″N, longitude: 108°1′39″E) on August 6, 2022. The picked apples, from a sample of 100, had an average diameter of 70.0±4.2 mm with a digital display Vernier caliper (0.02 mm divisions) and an average weight of 146.1±30.0 g with an electronic scale (0.1 g divisions).

2.2 Construction of platform for collision of fruits in the air

A platform was designed to simulate the collision of fruits in the air during vibration harvesting. The platform mainly consists of two arc panels (the left and right), two pneumatic vacuum suction cups (the left and right), two distance adjusters (the left and right), a mirror, a suction device, a fruit protector, and a high-speed digital video camera, as shown in Figure 1. The mirror was set at an angle of 135° to the plane where two arc panels were located to obtain three-dimensional displacements of fruit. Wu et al.[16] constructed a similar platform for the analysis of kiwifruit collision, in which kiwifruit was grabbed and released by electromechanical grippers due to its rough surface. In this study, a pneumatic vacuum suction cup, made of flexible material to avoid fruit damage, was utilized to fix and release apples due to their smooth surface. The adjustable suction cups were positioned using distance adjusters to control the release points. When the suction device lost suction, two fruits rolled off in respective arc panels at the same time and collided with each other in the air.



Note: A. Suction device; B. Arc panel; C. Distance adjuster; D. Mirror; E. Fruit protector; F. High-speed digital video camera; G. Pneumatic vacuum suction cup.

Figure 1 Platform for the collision of fruits in the air

Thus, preliminary tests determined a distance of 240.0 mm between two arc panels to ensure that fruits collide with each other in the air. The collision angle, the angle between the arc panel and the horizontal plane, was set to 30° to make the fruit roll down in the arc panel and collide in the air[17]. Two fruits fell into the fruit protector after the collision, which contained sponges and fillers to avoid secondary damage. The high-speed digital video camera (OLYMPUS i-speed TR; Keymed 'Medical & Industrial Equipment' Co., Ltd., UK) was used to capture the collision of fruits in the air. The resolution and frame rate of high-speed digital video cameras were set to 1280 pixels×1024 pixels and 750 fps, respectively.

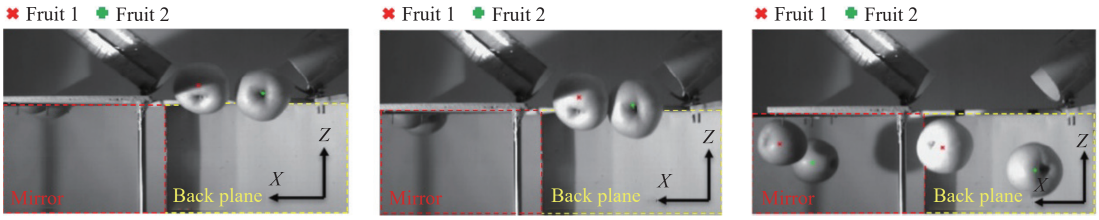
2.3 Theoretical calculation of CoR

The CoR, a common measure of kinetic energy loss, reflects the recovery ability of colliding objects during collision. Based on the deformation of fruit during the collision, a theoretical formula for CoR was derived. Equation (1) considers the velocities of fruits before and after the collision, and the restoring forces generated by fruit deformation, which are equal in magnitude and opposite in direction according to Newton's Third Law[16]. Subscripts 1 and 2 in Equation (1) indicate the pairs of fruits involved in the collision. Superscripts pre- and post- in equations represent the velocity of fruit before and after the collision, respectively.

$$e = \frac{\left|(v_2^{post} - v_1^{pre}) \cdot (v_2^{post} - v_2^{pre})\right|}{\left|(v_2^{pre} - v_1^{pre}) \cdot (v_2^{post} - v_2^{pre})\right|} \tag{1}$$

2.4 Acquisition and processing of collision velocity

Three-dimensional displacements of fruit were obtained by the mirror reflection principle. The mirror was added to the platform at an angle of 135° to the backplane to obtain three-dimensional displacements instead of just X and Z directions. The high-speed digital video camera, fixed vertically in front of the backplane, captured the fruit movement. The collision process recorded by the camera was handled by i-SPEED Suite software. The Y-direction displacement was derived from the reflection of a mirror, while X and Z displacements were directly obtained from the front view. Figure 2 shows the images of colliding fruits in the air in the mirror taken by the camera. Pre-collision and post-collision velocities were calculated from these fruit displacements. Since the arc panel restricted the *Y*-direction motion, pre-collision velocity in the *Y*-direction was 0.



a. Fruits before collision b. Fruits during collision c. Fruits after collision

Figure 2 Images of collision of fruits in the air and the mirror taken by high-speed digital video camera

2.5 Test design for collision of fruits in the air

According to the collision of fruits in the air during vibration harvesting, collision velocity *v* was selected as the test factor and changed by using the distance adjuster. The platform was developed to simulate the collision of fruits in the air. Therefore, there should be a correlation between collision velocity as a test factor and the initial velocity of the fruit separate from the branch, i.e., excitation energy obtained by vibration. The velocity of 1.0 m/s was calculated from the acceleration of fruit shedding during vibration harvesting. For this study, collision velocities were selected from 1.0 m/s to 2.0 m/s with a gradient of 0.2 m/s. The experiment was repeated six times for each collision velocity, with two apples tested in each instance. Each fruit was collided only once, avoiding the interference of multiple collisions to measure damage.

2.6 Fruit damage measurement and quantification

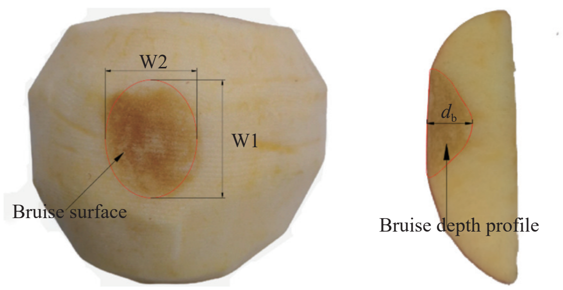
After collision tests, bruise volume was used to quantify fruit damage. Total bruise volume, the sum of bruises on both fruits, was selected to assess the damage severity. Fruits were left at room temperature for 48 h to make the bruise area visible by discoloration. Afterward, the skin was removed to measure the bruise surface area. The bruise volume of fruit was measured by the 'enclosed volume' method, developed by Holt and Schoorl[18]. Bruise volume for fruits was determined by assuming the bruise surface as an elliptical shape. The bruise surface A_b after peel removal was calculated using the elliptical surface described by Equation (2). The bruise volume *V* in the elliptical shape was calculated by Equation (3), with the parameter d_b measured using a digital Vernier caliper with an accuracy of 0.01 mm. The bruise surface and depth profile of fruit bruises were circled by enclosed red solid lines, as shown in Figure 3.

$$A_b = \frac{\pi w_1 w_2}{4} \quad (2)$$

$$V = \frac{\pi d_b}{24}\left(3 w_1 w_2 + 4 d_b^2\right) \quad (3)$$

where, w_1 refers to the major axis of the ellipse, mm; w_2 refers to the minor axis of the ellipse, mm; d_b refers to the depth of the bruise, mm.

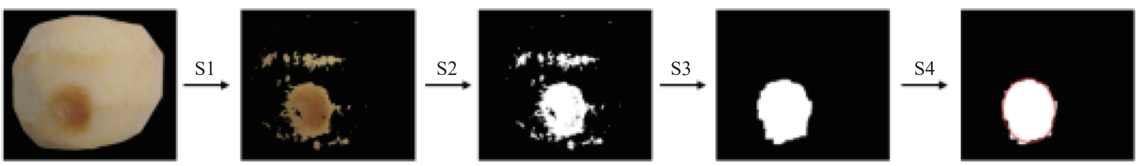
The major and minor axes of the bruise surface described in the elliptical shape were measured by image analysis. Since the bruised surface was irregularly shaped, it is difficult to obtain the major and minor axes of the approximate ellipse accurately by digital Vernier caliper measurement. RGB (Red, Green, and Blue) images of bruise surfaces were obtained using Azure Kinect DK camera (MIC2574, Microsoft Inc., Redmond, WA), which was attached to a support frame. The camera lens was parallel to the plane where fruit was located, and 210.0 mm from the plane. The original files were in .png format with a resolution of 4096×3072 pixels and a corresponding FOV (Field of View) of 90°×74.3°. Before image analysis, the background of these original images was removed by Adobe Photoshop CC 2018 (V19.1.9, Adobe Inc., San Jose, California, USA) to make them transparent. Programs were executed on a computer equipped with a 12th generation Intel(R) Core(TM) i5-12500H processor operating at 3.10 GHz, 16 GB of memory, and Windows 11 (10.0) operating system.



a. Bruise surface b. Bruise depth profile

Figure 3 Schematic diagram of parameter measurement of damage volume

The image analysis process consisted of four steps (S1, S2, S3, and S4) to extract and analyze bruise surfaces, as shown in Figure 4. In S1, the image was transformed from RGB to $L^*a^*b^*$ color space, focusing on the b^* channel to highlight intensity variations in the bruise for extraction. S2 applied the Otsu method to convert the grayscale bruise surface into a binary image for morphological manipulation. S3 employed morphological opening to remove noise and artifacts from the binary image while preserving the overall shape and structure of the bruise. Finally, S4 involved fitting the bruised surface to an ellipse to obtain the number of pixels occupied by the major and minor axes of the ellipse.



a. Fruit RGB image b. RGB image of apple bruise surface c. Binarized image of bruise surface d. Binarized bruise surface image after using morphological opening e. Ellipse fitting image of bruise surface

Figure 4 Image analysis process

The bruise surface was calculated from the number of image pixels and unit pixel size. The unit pixel size, which refers to the physical size of each pixel in the image sensor of the camera, was calculated based on external parameters of the Azure Kinect DK camera, including the camera resolution, angle of visual field, and photograph distance. The unit pixel size was calculated by Equation (4). The bruise surface was obtained by multiplying the number of pixels occupied by the major and minor axes of the fitted ellipse by the unit pixel size.

$$B=\frac{2\times d\times\tan\frac{FOV_H}{2}}{IM_H} \tag{4}$$

where, d refers to the camera mounting height, mm; FOV_H refers to the camera horizontal view angle; IM_H refers to the horizontal resolution of the image.

3 Results and discussion

3.1 CoR versus collision velocity for collision of fruits in the air

The CoR decreased with an increase in collision velocity from 1.0 m/s to 1.4 m/s, likely due to higher collision force leading to greater fruit deformation and energy loss. This aligned with findings from Stropek and Gołacki[19] for pears and Zeebroeck et al.[20] for tomatoes. However, when the collision velocity exceeded 1.4 m/s, as shown in Figure 5, CoR did not continue to decrease as expected. This irregularity may be attributed to the fruit rotation during the collision, as suggested by Ji et al.[21], who found that rotation can influence CoR.

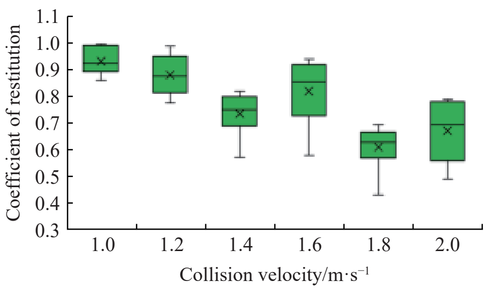
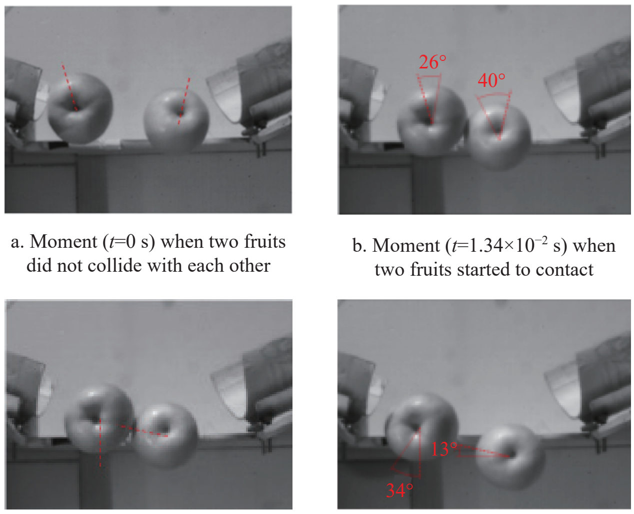


Figure 5 CoR for the collision of fruits in the air versus collision velocity

In contrast, previous studies that did not involve fruit rotation showed a decrease in CoR with increasing collision velocity. Dintwa et al.[22] constructed a finite element model to study the collision of two apples, where fruits were not rotated. One fruit was fixed while the other collided with it at varying initial velocities, similar to the collision between collected fruits and falling fruits. They found a linear decrease in CoR with increasing collision velocity, based on the fact that the fruit did not rotate because of the ground's support force during the collision. Pang et al.[21] investigated a free normal collision between a pair of Granny Smith apples hanging from two pendulums, where fruits were not rotated under the binding forces of the pendulum, similar to the collision between fruits on branches. In the absence of rotation, they observed that CoR varied nonlinearly and decreased with increasing impact energy.

However, this study differed by including rotation in the collision process since the fruit was not subject to support or binding forces. For example, at a collision velocity of 1.6 m/s, the CoR was 0.82. As shown in Figure 6, before the collision, the rotation angles of the two fruits were 26° (left) and 40° (right), and after the collision, they were 34° (left) and 13° (right). The angular velocities of the two fruits at contact were 34.12 rad/s (left) and 52.49 rad/s (right), and at detachment, they were 44.62 rad/s (left) and 17.07 rad/s (right). This suggested that rotation was involved in the collision, which may increase CoR[21]. The change in CoR from 0.74 at 1.40 m/s to 0.82 at 1.60 m/s, contrary to the expected decrease in previous studies, was due to the rotation, which could redistribute collision force, reduce the energy loss by deformation, and increase CoR. Therefore, rotation affected the regularity between collision velocity and CoR.



a. Moment (t=0 s) when two fruits did not collide with each other

b. Moment (t=1.34×10^{-2} s) when two fruits started to contact

c. Moment (t=1.6×10^{-2} s) when two fruits started to detach

d. Moment (t=2.94×10^{-2} s) when two fruits detached

Figure 6 Fruit rotation images for collision of fruits in the air taken by high-speed digital video camera

3.2 Fruit bruise

Bruise did not occur on fruits at the collision velocity of 1.0 m/s corresponding to a CoR of 0.93 but did at 1.2 m/s corresponding to a CoR of 0.88, and did not change regularly with increasing collision velocity. When collision velocity was approximately 1.0 m/s, the CoR reached 0.93 or higher, making fruits not bruise. Stropek and Gołacki[23] observed that apples started to bruise at collision velocities of 0.5 m/s, probably due to differences in collision methods and fruit varieties. Thus, the bruise velocity threshold for the fruit-to-rigid surface collision was smaller than fruit-to-fruit collision. The mean and standard deviation of total bruise volume increased gradually overall with the increasing collision velocity. When collision velocity increased from 1.4 m/s to 2.0 m/s, corresponding total bruise volumes were 359.65 mm^3, 361.17 mm^3, 477.28 mm^3, and 385.01 mm^3. This variation may be attributed to the conversion of translational energy, which contributes to fruit bruising, into rotational energy of different magnitudes during each midair collision between fruits[24]. Therefore, the total bruise volume changed irregularly. However, the dispersion of total bruise volume increased because of the overall increase in standard deviation from 0.00 to 272.47 mm^3, possibly making little correlation between CoR and total bruise volume.

There was little correlation between total bruise volume and CoR on account of composite motion of fruits. A logarithmic function was used to fit the data and describe the correlation between total bruise volume and CoR[17]. The R^2 determination coefficient of CoR on total bruise volume was 0.005, as shown in Figure 7, which indicated little correlation between the two, possibly due to the composite motion of fruits when fruits collide in the air.

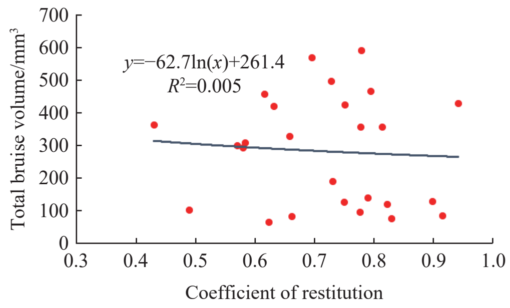


Figure 7 Total bruise volume versus CoR

During the movement, fruits made a composite motion combining translational motion and rotational motion. The energy corresponding to the two types of motion is called translational kinetic energy and rotational kinetic energy, respectively. Experimental findings from the pendulum showed that the fruit bruise decreased with the increasing CoR because an increase in CoR could mean a decrease in the collision energy absorbed by the fruit[19]. Total bruise volume reflects the energy absorbed by fruits during the collision[18], which refers to the translational energy rather than rotational kinetic energy. The formula of CoR only reflects the translational energy and not rotation. Thus, the CoR and total bruise volume only reflect translational motion, but not rotational motion during the collision.

However, fruits exhibit both translational and rotational motion under the method for collision of fruits in the air, which may be the reason for the different results from previous findings. Collision experiments using the pendulum method by Pang et al.[25] and Li and Wang[26] showed that bruise volume varied nonlinearly and decreased with increasing CoR, where fruits hardly rotated under the binding forces of strings before and after the collision. Therefore, under the pendulum method, fruits only made a translational motion during the collision, rather than the composite motion observed in this study.

Similarly, experiments by Wu et al.[16] and Fu et al.[17] obtained a similar conclusion, where fruits did not rotate before the collision and rotated slightly after the collision. Fruits made a translational motion before the collision and a slight composite motion after the collision, rather than a composite motion all the way during the collision as in this study. Therefore, the CoR may not be an indicator to determine the degree of fruit bruise when the object makes a composite motion during the collision. Since fruits can be removed by one or a combination of multiple motions such as pendulum, tilt, and rotation motions, there is usually a composite motion during vibration harvesting. The rotational motion should be considered in fruit-to-fruit collisions in future studies. In this study, three-dimensional translational motion of fruit can be obtained through the mirror, but three-dimensional rotational motion cannot. Thus, it has the potential to obtain three-dimensional rotational motion by marking the fruit surface in future studies to enhance the relationship between CoR and fruit bruise.

4 Conclusions

Collision of fruits in the air for vibration harvesting was achieved by designing a platform, where collision velocity influenced CoR. The CoR decreased with collision velocity increasing from 1.0 m/s to 1.4 m/s, because the collision force increased with collision velocity. However, when the collision velocity exceeded 1.4 m/s, the CoR did not continue to decrease with increasing collision velocity due to rotation. Image analysis based on RGB to $L^*a^*b^*$ conversion was used to extract the bruise surface to calculate bruise volume. No bruise was observed on the fruit at a collision velocity of 1.0 m/s and a corresponding CoR of 0.93. The fruit began to bruise as the collision velocity increased from 1.2 m/s. However, there was little correlation between CoR and total bruise volume due to the composite motion of fruits during the collision. The CoR may not have accurately reflected the degree of fruit bruise when the object made a combination of translational and rotational motion during the collision. Therefore, when analyzing and designing vibration harvesting machinery, the three-dimensional rotational motion of fruits should be considered to improve the prediction of fruit bruises.

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