FRUIT VIBRATION HARVESTING TECHNOLOGY AND ITS DAMAGE. A REVIEW
/
果品振动收获技术及其果实损伤-综述

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ABSTRACT

Manual harvesting of large area fruits is inefficient, which consumes manpower and resources. Mechanized harvesting is the inevitable trend of fruit harvest. Vibration harvesting is one of the important forms in terms of fruit mechanized harvesting. According to the different striking parts of fruit trees, the vibration modes were classified as trunk, crown, and branch types. The harvesting efficiency of fruit is an important index to measure the quality of all fruit harvesting machines. The reduction of fruit damage is considered in the harvesting of vulnerable fruits. In this study, the development of vibration harvesting technologies were studied in terms of vibration mode. The development of fruit damage, harvesting efficiency, and fruit tree modeling were discussed. Finally, the development direction of fruit vibration mechanized harvesting was looked forward. Machinery instead of manpower, fully mechanized harvesting is the inevitable development direction of fruit harvesting.

摘要

人工收获大面积果品效率低下，耗费人力，浪费资源。机械化收获是果品收获的必然趋势，振动收获方式是果品机械化收获的重要形式之一。按对果树打击部位的不同位置，对振动方式进行分类，包括树干、树冠、树干三种振动方式。果实的收获效率是衡量所有果品收获机械优劣的重要指标，易损果实的收获还需考虑降低果实损伤。本文从振动方式（树干、树冠、树干）综述了振动收获技术的发展历程以及发展现状，分别对果实损伤分析，收获效率分析以及果树建模分析的发展现状作出综述,并做出总结评论。最后，对果品振动式的机械化收获发展方向进行展望。机械代替人力，全机械化收获是果品收获的必然发展方向。

INTRODUCTION

Fruit is the essential food in human daily life, which plays an important role in the human dietary structure. Human demand for fruit is increasing. All kinds of fruits are grown in huge areas worldwide. Moreover, fruit harvesting is the most critical part of the whole fruit production process. It is a labour-intensive work with strong seasonality. In the fruit production process, the labour force accounts for 30%-45% (*Chen Du et al, 2011*). If they are not harvested timely, it will directly affect the quality of fruits and cause a lot of economic losses. Mechanized harvesting is the best way for fruit production. It can not only reduce production costs, save resources, but also improve production efficiency and improve fruit quality.

At present, compared with the other crops, the development of mechanized harvesting for fruits is slow. There are fewer machines used in actual production. In the process of research, improving harvesting efficiency and reducing fruit damage are two major problems. Vibration harvesting is one of the important forms of fruit harvesting. It is of great value to improve the production efficiency and reduce the damage rate to study the harvesting machine with different vibration forms.

In this study, the development status of vibration harvesting technology was discussed. The development of fruit damage, harvesting efficiency, and fruit tree modeling were summarized. Finally, the prospect of fruit vibratory mechanization harvesting development direction was analysed.

PRINCIPLE AND STATUS OF VIBRATORY HARVESTER

The principle of vibration harvesting is that the fruit trees are shaken by a vibration device. Then the fruit trees will vibrate with a certain frequency and amplitude.

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When the inertia force is greater than the binding force of the fruit handle, the fruit stalk will break, and the fruit will fall off. There are three types of vibration: trunk vibration, crown vibration, and branch vibration (*Sanders, 2005; Li et al, 2011*).

Branch vibration harvester

The principle of the branch vibration is to use the clamping device to hold the branch with fruit, and to use the crank connecting rod mechanism to achieve the effect of vibrating the branch, so that the fruits and branches are separated. As shown in Fig.1, the prototype of a hand-held jujube harvester designed (*Meng, 2014*) drives an eccentric vibration mechanism to enable the forward clamp head to reciprocate back and forth.

Fig. 1 - Prototype of hand-held jujube harvester

At present, this kind of harvester has a simple structure and relatively perfect development. For example, *Adrian et al* designed the first inertial shaker for citrus harvesting in 1965. *Yibo Ma* et al developed a dual motor-driven hand-held fruit harvester in 2018. The device includes a chuck, a motor-driven exciter, a controller, and a battery pack, which can adjust the operating frequency and excitation mode (*Ma et al, 2018*). However, this kind of harvesting machine is only suitable for harvesting a single or small number of fruit trees in the family. and is not suitable for large-scale harvesting.

Crown vibration harvester

The vibration harvesting of tree crown is to hit the tree crown by percussion device to achieve the effect of tree branch vibration and separate the fruit and branches. At present, compared with the tree branch and trunk vibration harvester, the crown vibration harvester is not perfect. Fig.2 shows the harvesting mechanism of the tree crown vibration harvester, which drives the lever roller to move horizontally or vertically to achieve the purpose of tree crown vibration. Fig.3 shows the self-propelled dwarf close planting jujube harvester; Fig.4 shows the straddle coffee harvester; Fig.5 shows the enclosed raspberry vibration harvester.

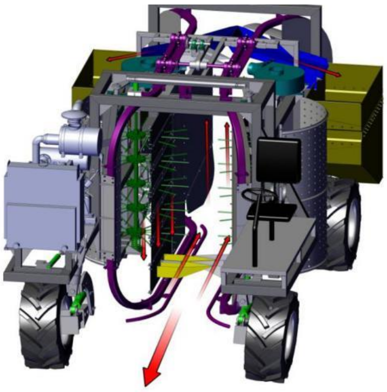


Fig. 2 - Harvesting mechanism of the tree crown vibration harvester

Fig. 3 - Self-propelled dwarf close planting jujube harvester

Fig. 4 - Straddle coffee harvester

Fig. 5 - Enclosed raspberry vibration harvester

The crown vibration harvesting is suitable for large-area fruit harvesting, which can significantly save manpower and improve efficiency. The method is suitable for fruits, which are not easy to be damaged, such as walnut, jujube, etc. However, the fruit will be damaged seriously during the beating process, which will reduce the economic and edible value. Therefore, it is still difficult to harvest vulnerable fruits and reduce fruit damage.

Trunk vibration harvester

Trunk vibration is to use the clamping device to clamp the trunk part of the fruit tree and then vibrate the trunk to achieve the vibration of the fruit tree, so that the fruit and branches are separated. At present, development is relatively perfect. Fig.6 shows the model of vibration harvesting system (*Luo et al, 2017*). Its principle is to drive an eccentric rotating mechanism or crank slider mechanism to make the vibrating head vibrate repeatedly. When the trunk vibrates, the mechanical energy is transferred to the fruit. Fig 7 shows the walnut tree shaking machine. Fig. 8 shows the 4ys-24 red jujube harvester (*Tang et al, 2010*).

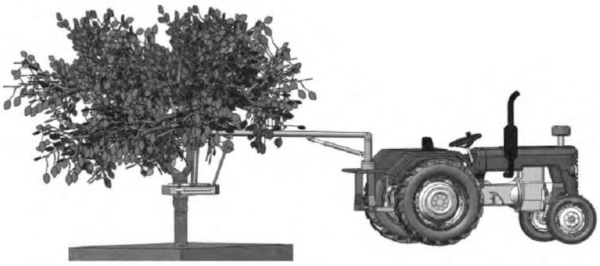


Fig. 6 - Model of vibration harvesting system

Fig. 7 - Walnut tree shaking machine

Fig. 8 - 4ys-24 red jujube harvesting machine

The clamping vibration harvesting machine has been applied in practice. It has high harvesting efficiency, which can save a lot of manpower and material resources. The method is suitable for harvesting fruit on a single tall tree. For example, FMC-400, a citrus harvesting machine designed, works on the principle of reciprocating movement of the clamping head to achieve the purpose of tree trunk vibration. However, the clamping vibration machine is only suitable for single fruit trees, not for the large-scale and large-scale fruit harvesting.

Table 1

Comparison of different harvesting methods

Harvesting way	Suitable type of fruit tree	Advantages	Disadvantages
Branch vibration harvester	Single fruit tree	Simple structure, easy operation, and low cost	Low harvesting efficiency
Crown vibration harvester	Suitable for large area dwarf dense planting fruit trees	Full mechanization, high efficiency, can complete a large area of fruit harvesting	Complex structure, easy to cause fruit damage
Trunk vibration harvester	Single fruit tree (tall, thick)	Full mechanization, high harvesting efficiency, can complete high tree harvesting	Complex structure, not suitable for a large-scale, large area of fruit harvesting

Table 1 shows the comparison of different harvesting methods. Tree branch vibration harvesting is the most popular method in practical production and application at present.

However, compared with the other two methods, the harvesting efficiency is low. Fruit tree planting can gradually develop into large-scale planting mode, so the tree branch vibration harvesting mode is a transitional stage of mechanized fruit harvesting. The trunk vibration harvesting method is suitable for tall, single trees with thicker trunks. Under the planting mode of large-area dwarf dense planting, crown vibration harvesting mode is the mainstream direction. Still, this kind of mechanical structure is complex, how to reduce fruit damage in the harvesting process is a problem. At present, this kind of method is rarely used in the actual harvesting, basically in the theoretical test stage.

FRUIT HARVESTING EFFICIENCY

Harvesting efficiency is one of the important indexes to measure the harvesting quality. The factors that affect the efficiency mainly include vibration frequency, amplitude, and exciting position.

Fruit harvest

There are many related researches on fruit harvesting efficiency. Scholars have done a lot of research on the cherry harvesting. These studies mainly focused on energy transfer efficiency with different vibration frequencies. Different excitation positions were used to test the fruit removal rate. It was concluded that the farther away from the excitation position, the higher the fruit removal rate. The dynamic response of cherry trees under vibration was studied. The frequency of 2-40hz was used to obtain the resonance frequency of tree vibration. The results showed that the cherry tree with simple structure and few branches had higher harvesting efficiency (*He et al, 2013; Zhou et al, 2014; Du et al, 2010*). The effects of frequency, excitation location and branch structure of fruit trees on harvesting efficiency were analysed. The main movement patterns of cherry during shedding were studied by high-speed camera. It can provide reference for the design of cherry harvester. But the vibration excitation system of fruit trees is complex. In the actual harvesting process, many external factors have not been considered. Fig. 9 shows the cherry harvesting analysis test.

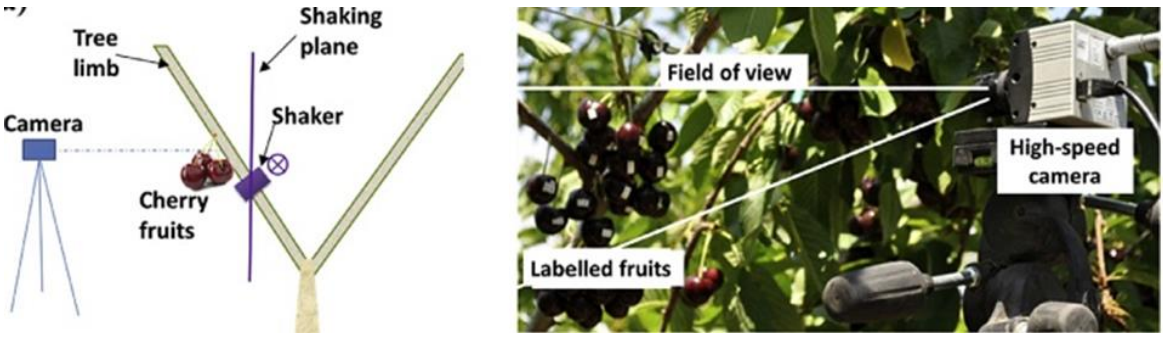


Fig. 9 - Cherry harvesting analysis test

To improve the efficiency of the mechanical harvesting apple, *Liu et al* designed a harvesting mode for high fruit trees. The results showed that when the change rate of vibration frequency was 8Hz, a higher harvesting rate could be obtained. When the frequency was greater than 12Hz, the harvesting rate was higher than that of the traditional fixed frequency harvesting mode (*Ming et al, 2018*). The experiment showed that it was feasible to harvest apple with a frequency conversion mode, which provided a new method for fruit harvesting mode.

Hamidreza H et al took olive as the object, simulated the influence of vibration frequency, loading mode, and loading height on the olive harvest. They compared the simulation results with field test results, and carried out an accurate 3D analysis of mechanized olive harvesting (*Hoshyarmanesh et al, 2017*). The ideal harvesting parameters and harvesting efficiency were obtained. Rafael R et al made a study on the dynamic response of olive trees with vibration parameters. 44 points were randomly measured on the tree with different heights from the ground. The dynamic response and vibration characteristics of the olive tree under different vibration parameters were analysed. This study provides a reference for the design of straddle olive harvester and is also applicable to other similar harvesting machines. Fig.10 shows the dynamic response test analysis of olive (*Sola Guirado et al, 2019*).

Peng et al studied, on winter, jujube harvesting, and analysed the dynamic response of jujube trees under different frequencies (5, 10, 15, 20, 25 Hz) with finite element method, and found the relation between acceleration and frequency (*Peng et al, 2017*).

Liu et al studied the influence of vibration frequency on citrus fruit abscission, then obtained that vibration frequency and penetration depth had extremely significant effects on fruit removal efficiency (*Liu et al, 2018*). *Spain A. et al* obtained the influence law of vibration frequency and other parameters on citrus fruit abscission, and obtained that almost all fruits can fall off with the amplitude of 15Hz and the vibration time of 5s (*Torregrosa et al, 2009*). This study provided a reference for the design of mechanical parameters of tree trunk vibration harvesting, but the problem of fruit damage was not considered in the experiment. The high-speed camera and the image processing method can analyse the movement of citrus in the vibration harvesting process, and better understand the vibration separation mechanism of citrus and other fruits. *Torregrosa A. et al* studied the vibration response of citrus fruit. The vibration rod had an amplitude of 60~180mm and a frequency of 3~18Hz. Based on the high speed camera, the main parameters of fruit detachment were determined (*Torregrosa et al, 2014*). *Castro-Garcia et al* applied the experiment on 22 secondary branches of Valencia sweet orange. In the branch, three natural frequency values were determined, which were 2, 7 and 11Hz respectively. The effects of fruit and leaf on the dynamic response of secondary branches were studied (*Castro-Garcia et al, 2020*). The results were as follows: in the process of mechanical harvesting, the number and quality of leaves and fruits of fruit trees had an important impact on the harvesting efficiency, which provided a reference to optimize the parameters of harvesting machinery.

Erdogan D et al studied the mechanical harvesting of apricot with the amplitude of different distance (20, 30, 40, 50, 60 mm) then the vibration frequency of 10, 15, and 20 Hz, and studied the influence of vibration parameters on the harvesting efficiency (*Erdoğan et al, 2003*). It provided a reference for the parameter design of the inertial vibration device. *Pezzi F. et al* used five frequency settings to record the grape yield, Furthermore, they studied the vibration transmission in the process of grape mechanized harvesting (*Pezzi et al, 2009*). *Wang et al* studied the vibration harvesting efficiency of litchi and found that 90% of the fruits shed at the speed of 1.2s, 0.9s, and 0.5s at 18Hz, 25Hz, and 32Hz, respectively (*Wang et al, 2019*). *He et al* developed an intelligent vibrating screen system to measure the multiple natural frequencies of fruit trees. It also conducted an acceleration response test under different vibration frequencies to obtain the optimal vibration frequency (*He et al, 2020*). Table 2 shows the analysis of the harvesting efficiency of some fruits.

Fig. 10 - Dynamic response analysis test of the olive tree

Table 2

Analysis of fruit harvesting efficiency test (some fruits)

Fruits	Factors affecting the	Conclusion	Reference
Cherry	Frequency	The fruit removal rate was higher at the frequency of 18Hz.	*(He et al, 2013; Zhou et al, 2014; Du et al, 2010)*
	Vibration position	The farther the distance from the excitation location, the higher the fruit removal rate in each region.	
Apricot	Frequency	In the amplitude of 40mm, the frequency of 15hz vibrating screen work can be the greatest degree of fruit.	*(Erdoğan et al, 2003)*
	The amplitude		
Litchi	Frequency	90% of the fruits were fruited at 1.2s, and 90% of the fruits were fruited at 1.2s, 0.9s, and 0.5s at 18Hz, 25Hz, and 32Hz, respectively.	*(Wang et al, 2018)*
Citrus	The amplitude	With an amplitude of 15Hz and a vibration time of 5s, almost all the fruit can be shed.	*(Torregrosa et al, 2009)*
	Vibration time		

Yang et al studied the influence of vibration time, vibration frequency, and amplitude of vibration excitation point on vibration acceleration of apricot tree. Moreover, the dynamic response during the apricot abscission process was studied. They established response equations of different test points, and optimized multi-objective parameters. (*Yang et al, 2019*). *San et al* studied the influence of vibration mode and frequency on the vibration harvesting response of apricot trees. Through the vibration transmission upward from the clamping position along the trunk, the acceleration vibration response curves of different positions were obtained. At the same time, it was concluded that the acceleration value of each detection point was the maximum when the apricot tree was excited by 11.56 Hz. (*San et al, 2018*). The research provides theoretical reference for the design of apricot or other fruit harvesting machine parameters.

Yang made a study on the mechanical harvesting of dwarf and dense planting jujube. Taking the fruit removal rate as the index, the parameters of the harvesting parts and dense planting jujube harvesting device were designed. The parameters were optimized by orthogonal test, and the parameters of the optimal fruit removal rate were obtained (*Yang, 2013*).

Huo established the vibration model of the blueberry picking system. The frequency, amplitude, time, and area of action were taken as the factors affecting the efficiency of blueberry picking. The primary, secondary order, and the optimal combination of picking parameters were obtained through simulation, (*Huo, 2013*). Ding carried out research on mulberry fruit abscission characteristics. Then they studied the main influencing factors of inertial force during mulberry vibration picking, obtained the vibration parameters of vibration picking device when mulberry fell off and designed a portable mulberry vibration picking device according to the experimental parameters (*Ding, 2016*).

Many scholars have studied the harvesting efficiency of mechanized harvesting fruits. However, there are still problems. First of all, most of the experiments extract part of the parameter values for research; whether the parameter values beyond the test value range can get better optimization results is still to be discussed. Secondly, the effects of the harvesting season, environmental factors, and fruit tree parameters were not considered. However, the experiment of large-area and large-scale fruit harvesting efficiency has been done less, so this kind of experiment is still a big problem.

Non-fruit harvesting

There are also related studies on the harvesting efficiency of pistachio and walnut. *Polat et al* studied the effect of vibration frequency and amplitude on pistachio fruit harvesting. The amplitudes of 40, 50 and 60mm and the frequencies of 10, 15 and 20Hz were adopted. The optimal amplitude was 50mm and the optimal frequency was 20Hz. It was concluded that the efficiency of mechanical harvesting was far greater than that of manual harvesting. Through the comparison between manual harvesting and mechanical harvesting, it was concluded that the inertia vibrating screen is feasible. The influence of fruit tree structure on the test results was fully considered (*Polat et al, 2007*).

Wang et al applied different harvesting methods to analyse the harvesting efficiency of *Lycium barbarum* fruit. The results showed that the picking rate reached 85%, while the fruit damage rate was low (*Wang et al, 2018*). It is the best method to harvest the *Lycium barbarum* by vibration.

Du et al analysed the different incentive modes produced by the combination of different eccentric mass for dwarf Chinese hickories. It was concluded that orthogonal eccentric mass could effectively and evenly transfer vibration and improve harvesting efficiency (*Du et al, 2018*).

Ferreira et al studied the dynamic response of coffee tree during picking and obtained the frequency and amplitude of coffee tree vibration (*Ferreira et al, 2020*).

There are kinds of dried fruits and non-fruit fruits such as *Lycium barbarum* and coffee. However, compared with fruits, there are few studies on the harvesting efficiency of such fruits.

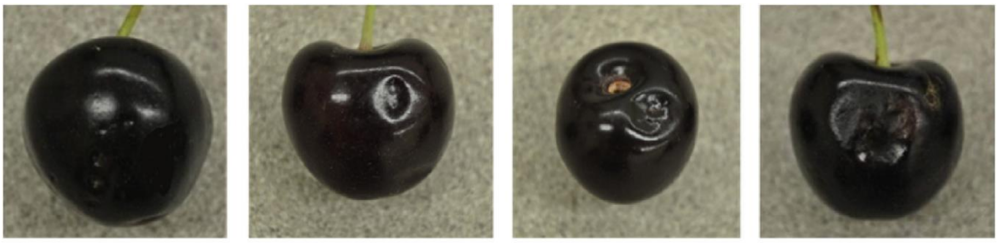
FRUIT DAMAGE

Mechanical damage will cause fruit aging, decay, loss of nutritional value, and greatly reduce the economic and edible value of the fruit. Therefore, for the mechanical vibration harvesting of fragile fruits, the damage of fruits is an important index. The influencing factors include vibration parameters, such as frequency, amplitude, etc., as well as the drop height, picking plate angle, and so on.

Vibration parameters

The parameters such as excitation frequency are the main factors affecting fruit damage for vibration harvesting. *Zhou et al* used a high-speed camera to capture 18 fruit trajectories at different frequencies, and concluded that the main motion modes were tilt and cylinder motion.

This experiment also analysed the movement pattern of cherry fruit during harvesting and its relation with fruit damage. As shown in Fig. 11, the cherry damage can be divided into four levels.



(a) *(b)* *(c)* *(d)*

Fig. 11 - Cherry damage grading

Cherry damage classification is shown in Table 3 (*Zhou et al, 2016*). *He L. et al* made the relevant research on the cherry damage principle. Four different excitation positions were used to test the fruit damage. The damage of different excitation positions from low to high was 20%, 28%, 20%, and 23% respectively. It was concluded that there was no significant difference in the damage of fruits at different excitation locations (*He et al, 2017*).

Table 3

Damage grading of cherry

Fruit	Number	Level	Damage	Reference
Cherry	a	Level 1 damage	There are small dents	(*Zhou et al, 2014*)
	b	Level 2 damage	There are depressions	
	c	Level 3 damage	The diameter of the damaged area is larger than 6.4mm	
	d	Level 4 damage	The diameter of the damaged area is larger than 9.5mm	

Wang et al made a study on litchi collision damage and found that when the vibration frequency was 32 Hz, the minimum damage degree was 5.69%. It was feasible to harvest litchi fruit with high speed and low damage under appropriate frequency (*Wang et al, 2019*). However, this test is a mechanical shedding test conducted in the laboratory, which does not consider the influence of environmental factors and fruit tree structure, which is a common problem in the current test.

Sergio Castro Garcia et al studied the use of vibrating tree trunk to harvest olive. To achieve 85% harvesting efficiency, acceleration greater than 183.4m/s^2 and vibration frequency of 28.1Hz is required. However, the damage of olive is 3.5 times that of manual harvesting (*Sergio Castro-Garcia et al, 2015*). *Pezzi F. et al* used five frequency settings, 370-450 times per minute, to record the loss of yield and plant defoliation. They studied the mechanical vibration transmission of mechanical harvesting grapes (*Pezzi et al, 2009*). The straddle type harvester was used to test, which provided a reference for the parameter design of the harvester.

Sergio Castro-Garcia et al analysed the abscission process of "Valencia" orange fruit, adopted low-frequency and high amplitude movement to improve the vibrating screen system to reduce the damage of trees and fruits in the process of harvesting. In this experiment, three different vibrating screens were applied to obtain the vibration frequency and vibration time during the fruit harvesting process, which can improve the harvesting efficiency and reduce the damage of the fruit. It provides a reference for the design of harvesting machine parameters (*Sergio Castro-Garcia et al, 2018*). *Han et al* designed a vibrating screen with an adjustable vibration amplitude for harvesting apple. The vibration frequency of 20Hz and the vibration time of 5 s was adopted. The results showed that the vibration amplitude of 30 mm was enough to make the fruit fall off and get high-quality fruit (*Han et al, 2019*).

Table 4, vibration parameters affecting fruit damage (some fruits). A large number of experiments showed that the vibration parameters affecting fruit damage include frequency and amplitude, while the excitation position had little effect on fruit damage. However, the appropriate frequency or amplitude can reduce the fruit damage in the harvesting process, and does not affect the harvesting efficiency.

Table 4

Vibration parameters affecting fruit damage (some fruits)

Fruit	Vibration parameters	Conclusion	Reference
Cherry	Frequency	At the vibration frequency of 10, 14, and 18, the fruit damage caused by 14Hz was at the lowest of 47.1%.	(*Zhou et al, 2016*)
Litchi	Frequency	The lowest average damage at 32Hz was 5.69%.	(*Wang et al, 2019*)
Apple	Amplitude	The fixed frequency was 20Hz and the vibration time was 5. Among the four amplitudes of 20, 25, 30, 35, and 40mm, the amplitude of 30mm could not reduce the harvesting efficiency and obtain high-quality fruits.	(*Han et al, 2019*)

Impact parameters

The drop height, impact angle, and other parameters also affect fruit damage. *Salarikia et al* used a drop test to analyse the dynamic characteristics of pear under impact load, to reduce the impact damage of pear during harvesting (*Salarikia et al, 2016*). *Stropek* selected two pear varieties as experimental materials to study the relation between the internal damage energy and the impact speed of pear. The result is that the higher the impact speed, the higher the internal damage energy (*Stropek et al, 2020*).

P. Komanicki et al analysed the impact of impact load on pear impact damage by measuring the surface pressure of pear under different drop heights and specific impact times (*Komarniki et al, 2016*). All of the above are aimed at the pear damage test. The influence of the drop height, impact times, and other parameters on the pear damage and the energy transfer in the process were analysed. It can not only provide a reference for pear damage reduction in the harvest process but also provide a theoretical basis for material damage principle in other production processes such as transportation.

Zhou et al studied the effects of fruit drop height and grip angle on cherry collision damage. The results showed that there was a positive linear correlation between fruit impact force and fruit drop height, and fruit bruise could be reduced when the tilt angle was 60 degrees (*Zhou et al, 2016*).

Wang et al took litchi as the research object. When the impact velocity was 2.8 m/s, 15 times of impact on the fruit was obvious, and 5 times of impact on the fruit damage was small. When the velocity was 0.98m/s, there was no obvious damage after 15 times of impact. So, increasing the impact speed or times would cause greater damage to the fruit (*Wang et al, 2018*). *Wang et al* used litchi fruits of "Nuomici" and "Guiwei" varieties as experimental materials to study the collision behaviour between fruit and rigid plate. With the increase of drop from 200 mm to 800 mm, the damage degree of litchi varieties increased. However, when the drop increased from 600 mm to 800 mm, "Nuomici" was more resistant to fruit damage than "Guiwei" (*Wang et al, 2020*). The studies showed that in addition to the impact parameters, there was also an important relation between the variety of fruit and the damage.

Öztekin et al carried out impact tests on Peach Cultivars of “Glohaven”, “J.H. Hale”', and “Loring”. Through the analysis of the relation among impact peak acceleration, impact velocity change and impact area, the damage boundary values of three peach varieties were determined (*Öztekin et al, 2020*).

Bao et al made a study on impact damage assessment of mechanically harvested blueberry fruit based on collision deformation energy. It was concluded that when the distance between the blueberry growth concentration area and blueberry harvester fruit plate was close to 600 mm, and the angle of the picking plate was close to 15^{o}, the impact deformation energy of fruit was less than 0.68×10-3J, and the fruit damage was the least (*Bao et al, 2017*).

Table 5m shows impact parameters affecting fruit damage. It can be seen from the relevant literature that the impact parameters of fruit damage mainly include fruit drop height, fruit drop angle, impact speed, and impact times. The purpose of changing the impact parameters is to reduce the impact load during the harvesting process and reduce the damage of the fruit. The height of fruit drop, impact speed, and impact times were positively correlated with fruit damage. Therefore, in the case of little effect on the fruit harvesting efficiency, the appropriate impact parameters can effectively reduce the fruit damage. At present, the purpose of relevant tests is mostly to find out the relation between relevant parameters and impact load. Therefore, the relevant impact parameters should be optimized in the experimental study to obtain the optimal impact parameters without affecting the harvesting efficiency.

Table 5

Impact parameters affecting fruit damage (some fruits)

Fruit	The impact parameters	conclusion	reference
Cherry	Fruit drop height	There was a linear positive correlation between the impact force of the fruit and the height of the fruit, which could reduce the bruising of the fruit when the tilt angle was 60°.	(*Zhou et al, 2016*)
	Tilt angle		
Litchi	Impact velocity	When the impact velocity was 2.8 m/s, the damage to the fruit was obvious in the 15 impacts, but less in the 5. When the speed was 0.98 m/s, no obvious damage was seen in the 15 impacts.	(*Wang et al 2018*)
	Number of impacts		

Colliding materials

Material is also an important factor affecting fruit damage. *Zhou et al* studied the effect of buffer materials on cherry damage. The thick enough cushion material could reduce the impact force of fruit and reduce the damage of fruit (*Zhou et al, 2016*).

Lin et al studied the effect of colliding material on peach damage by a vibration test. The results showed that PU +CFB was better than EPE + CFB and CFB as packaging buffer material (*Lin et al, 2020*).

Öztekin et al put three kinds of peach such as "Glohaven", "J.H. Hale" and "Loring" on three steel impacting surfaces that did not cover any material, and covered the porous plastic or rubber foam on the impact surface. The results showed that porous plastics could reduce the damage of fruit (*Öztekin et al, 2020*).

Fernando I. et al evaluated the effectiveness of two types of corrugated paperboard packaging, reusable plastic creates (RPC) and vacuum tightening for their protective performance in reducing damage of bananas under simulated transport vibration. (*Fernando et al, 2019*).

It can be seen that the study on collision materials in the harvesting process mainly include the fruit picking device and the hitting device. The changing on the materials is also to reduce the impact load of the fruit when contacting the fruit picking device and beating device. Selecting the appropriate flexible material through the test can effectively reduce the damage of the fruit in the harvesting process, and obtain high-quality fruit. The experiments can not only provide a reference for the selection of materials in the harvesting process but also provide a reference for the selection of other production process materials such as fruit transportation and packaging.

FRUIT TREE MODELING

Fruit tree modeling can analyse the dynamic response characteristics of fruit trees in the process of vibration harvesting, to provide a theoretical basis for the design of harvesting machinery. The accuracy of the test can be verified by comparing the modeling results with the test results.

Peng carried out the study on the vibration harvesting of winter jujube by modeling on the jujube tree. As shown in Fig.12, the tree model was divided into two parts of branch and trunk. The response of trees to vibration excitation was predicted. The relation between the response and the excitation frequency was studied. It was concluded that the changing trend of simulation and measurement was better (*Peng et al, 2017*). This method has certain reference value for studying the dynamic response of fruit trees under the excitation of the vibration device.

For the citrus harvest, *Liu et al* established a cantilever branch model with a periodic vibration force to simulate the vibration process of citrus canopy. The results showed that there was a positive correlation between the vibration frequency and the maximum stress at the end of the fruit stalk. When the vibration frequency was 5 Hz, the fruit could be removed (*Liu et al, 2018*). This method is aimed at the vibration process of the canopy and provides a reference for improving the design of the canopy vibration device.

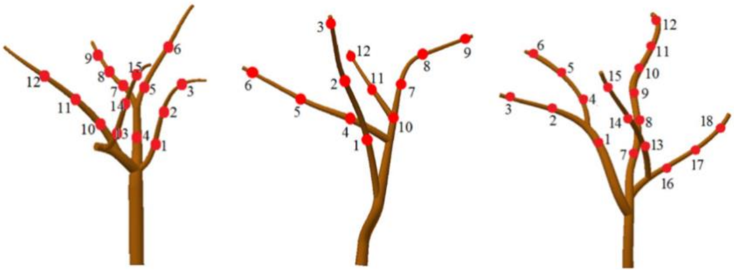


Fig. 12 - Three jujube tree models

Du et al established the finite element model of a dwarf Chinese hickory tree. Then, ADAMS software was used to analyse the model to simulate the response of a dwarf Chinese hickory tree to different eccentric mass combination excitation. It was concluded that the orthogonal eccentric mass could effectively and evenly vibrate the branches and improved the harvesting efficiency (*Du et al, 2018*).

Salarikia et al studied the impact damage of pears. The drop test was applied to analyse the pear samples by the finite element method. The pear model was made by non-contact optical scanning technology, and the simulation analysis was carried out on the three-dimensional entity (*Salarikia et al, 2016*). Using non-contact optical scanning technology to make a 3D model can not only detect and analyse the shape and appearance of real objects in detail but also avoid the tedious process of manual modeling.

Kursat Celik H. used the simulation method to analyse the damage sensitivity of Ankara pear to impact load (*Kursat Celik H., 2017*).

Du established the finite element model of kiwifruit falling and simulated the falling scene. It was concluded that the sensitivity of using the finite element method to predict fruit damage was reliable (*Du et al, 2019*).

Villibor et al established a flexible model of coffee fruit stem system for dynamic analysis. The model included oblique branch, fruit stem, and fruit. The fruit stem was modeled as a flexible beam and discretized into four elements (*Villibor et al, 2019*).

Yang et al studied the dynamic response of apricot tree vibration, established the model of the apricot tree by ANSYS software, obtained relevant parameters through finite element analysis (*Yang et al, 2019*), The results were shown in Figure 13. Wang et al applied three typical plastic fruit trees to establish fruit tree models. Then, the natural frequencies and modal shapes of the fruit trees in the low-frequency range of 1 ~ 50 Hz were obtained by using the finite element method.

The simulation test of vibration response characteristics was carried out (*Wang et al, 2017*).

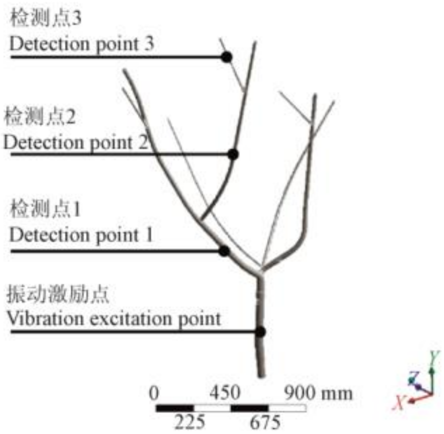


Fig. 13 - Finite element model of apricot tree established by Autodesk Inventor 2014

Bao obtained the theoretical value of deformation and deformation energy of blueberry through finite element simulation and studied the damage principle. It was concluded that the drop height and the angle of the fruit receiving plate were the main factors affecting the deformation energy of blueberry (*Bao et al, 2017*).

Through research on fruit tree modeling, it can be concluded that fruit harvest is dynamic rather than static. So, the modeling of fruit tree and fruit is dynamic model, the modeling must be a flexible model. Most of the researches adopt the method of finite element modeling. Through the method of fruit tree modeling, we can simulate the dynamic response characteristics of fruit trees in the process of vibration harvesting, predict the factors affecting the fruit picking efficiency, and analyse the damage mechanism of fruits in the process of picking. The simulation results can also be compared with the experimental results to further verify the accuracy of the test results. But the fruit system is very complex, mechanical harvest will be affected by many factors of fruit trees and fruit itself, such as the height of trees, the shape and size of fruit. There are many external factors in the process of harvesting, such as geographical and environmental factors. The results obtained by modeling may have some errors with the experimental results. How to improve the reliability and accuracy of fruit tree modeling needs further research.

DEVELOPMENT PROSPECT

Fruit vibration harvesting is the mainstream development of fruit mechanized harvesting. It is a kind of harvesting method with relatively high harvesting efficiency. Among the three harvesting methods, branch vibration harvesting is inefficient and will be replaced by full mechanization. Trunk vibration harvesting is suitable to harvest fruit on tall fruit trees, but it is not suitable for large-scale and large-area fruit harvesting. Crown vibration harvesting is suitable for large-scale fruit harvesting, but it is easy to cause fruit damage. Therefore, fruit vibration harvesting may have breakthroughs in the future:

(1) The main direction of fruit harvesting development in the future is a large-scale fruit harvesting. The crown vibration harvesting is the most suitable method, so the development of the crown vibration harvesting machinery should be strengthened. If the fruit tree trunk is thin, the application of crown vibration to the tree trunk can not only improve the harvesting efficiency of traditional tree trunk vibration harvester, but also reduce the damage of fruit.

(2) Make a breakthrough in improving the efficiency of fruit harvesting. Optimize the parameters of mechanical operation, to improve the efficiency of fruit harvesting and reduce the production cost.

(3) Make a breakthrough in reducing fruit damage. The mechanism of fruit damage was analysed. Without affecting the harvesting efficiency, the impact times and impact force of fruits were reduced, so as to reduce the damage of fruits. In the vulnerable fruit, the harvest aspect makes the breakthrough unceasingly.

CONCLUSIONS

The vibration harvesting for fruit is one of the development ways to realize the full mechanized harvesting of fruits. This research has been carried out for decades. At present, a lot of research has been done on apple, cherry, pistachio, and other fruits all over the world. A large number of patents on harvesting machinery have been obtained. But it is seldom applied in the production of harvesting machinery. At present, most of the machines are still in the theoretical stage. There is still a big gap between fruit harvesting and crop harvesting. There is still a long way to go to realize the full mechanized harvesting of fruits. We should carry out further research based on previous studies to promote the development of fruit mechanization.

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