Selection and experimental evaluation of shaking rods of canopy shaker to reduce tree damage for citrus mechanical harvesting

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Abstract: Canopy shaking system is one of the research hotspots for large-scale mechanized fruits harvesting. Shaking rods considered as one of the essential components of canopy shaker are responsible for transferring mechanical energy from shaking mechanism to different regions of tree canopy. This transfer depends on the characteristics of the shaking rods that directly strike the tree canopy. In order to evaluate the effects of the shaking rods on tree damage level and fruit removal percentage, three kinds of shaking rods with different materials or shapes were selected. Based on the results of bending deformation tests, it was proven that the rigid shaking rod (R_1) with the material of Polyvinyl Chloride (PVC) did more resistance against producing bending deformation in comparison with the other two types of shaking rods with the material of Polyamide Nylon 12 (PA). By contrast, the position close to the free end of the flexible shaking rod was easier to be deformed by less external force. In addition, dynamic analysis and vibration performance tests indicated that the rigid shaking rod could produce stronger vibration with higher shaking frequency of 4.8 Hz and maximum acceleration of 31.4 m/s^2. Finally, the results of field trials indicated that the flexible bow-shaped shaking rod (R_3) has a better widespread performance to achieve comparative higher fruit removal percentage up to 82.6% while producing lower tree damage rate of 5.36%. This study demonstrates that the materials or shapes of the shaking rod could significantly influence the fruit detachment rate and tree damage level. This study would provide an essential reference for the application of shaking rods for canopy shaker.

Keywords: citrus harvester, shaking rod, canopy shaker, bending deformation, tree damage, fruit removal
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1 Introduction

From 2016 to 2017, Florida was still the main orange producing area accounting for more than 58% in the US citrus industry in spite of continuing a multiyear downward trend according to the forecast released by the USDA Agricultural Statistics Board[1]. Most citrus harvesting was conducted by manual labor causing a large proportion as much as 35%-50% of the total production costs for citrus crops[2,3]. Until now, mechanical vibration as an effective citrus harvesting method is capable to significantly reduce labor costs and increase the harvesting efficiency[4,5]. It is feasible to employ a mechanical shaking system for mass citrus harvesting, because most orange production in Florida is used for juice processing industry without regard to fruit bruise[6]. So far, canopy shaking system compared to other mechanical shakers can get a fruit harvesting rate up to or more than 15 times higher than hand-picking[4,7]. Obviously, canopy shakers are the most efficient harvesters which can detach fruits continuously during the mechanical harvesting[8].

It is known that canopy shaker employs a series of shaking rods inserting into tree canopy and making the branches vibration with certain frequencies to detach fruits for harvesting. Currently, straight shaking rod is the most common configuration used for canopy shaker. For example, Peterson[9] developed a kind of double-spiked-drum canopy shaker equipped with total twelve whorls which had 16 straight nylon rods distributed at equal angle, respectively, which obtained mature fruit removal averaged 71% to 91% with shaking frequency of 4-5 Hz. Castro-Garcia et al.[10] introduced a canopy shaker employing three picking-heads with straight rubber rods for table olive harvesting at a frequency of 5.26 Hz, caused fruit damage up to 35% by the impact of rods and hard surfaces. Specifically, a continuous canopy shaker, using two self-propelled single drum shakers with 12 whirls where each whirl has 16 straight tines with the shaking frequency of 3 Hz to 3.8 Hz, has been manufactured by OXBO International Corporation (Byron, NY, USA) for commercial citrus harvesting[11,12]. Hong et al.[13] developed an experimental canopy rotary drum shaker which consists of a series of straight fiberglass rods with amplitude of 76.2 mm and frequency of 5 Hz to selectively harvest *Jatropha curcas* fruits without harmful severe damage. Yu et al.[14] introduced a rotary blueberry mechanical harvester (Korvan 8000, Oxbo International, Lynden, Washington, USA) mounted with two spindles of straight nylon shaking rods which could produce 25% mechanical impact on fruit. Sola-Guirado et al.[15] designed and

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developed a canopy shaker using 6 beating drums which has 24 straight shaking rods with the removal efficiency of 77.3%. In general, the above canopy shakers commonly used straight shaking rods to harvest fruits according to their experience but not analyzing the selection of the shaking rod.

In addition, bow-shaped shaking rod is also adopted in the development of canopy shaker for fruit mechanical harvesting. A self-propelled canopy grape harvester (VL6060 Braud, Morigny-Champigny, France) equipped with a beater using bow-shaped poles with frequency of 6.2-7.5 Hz, was developed to harvest grapes without excessive damage for wine industry[16]. A kind of towed grape harvester (Gregoire G60, designated T) and self-propelled grape harvester (Gregoire G152, designated S) installed with 14 mounting bow-shaped rods (7 rods for each side) on the beater were manufactured to harvest grapes continuously with higher productivity (>50%)[17]. Besides, a horizontal canopy shaker (Pulsar model, Tanesini Technology, Faenza, Italy) was equipped with a beater composed of two vertical series of curved rods with frequency of 5-9 Hz for grape harvesting[18]. It was clear that the above canopy shakers with bow-shaped shaking rods were mainly used for mechanical grape harvesting. There was no performance evaluation of the bow-shaped shaking rod for mechanical harvesting.

As we all know, canopy shakers can significantly increase the fruit removal efficiency, but it also produce a lot of debris simultaneously, especially the structural damage to the tree canopy. In order to reduce tree damage and increase the fruit detachment rate under canopy shaking, the application of abscission agents has been widely investigated to reduce the fruit-stem detachment force[19-23]. Previous studies on utilizing abscission chemical agents have indicated that the abscission chemicals can improve the selective detachment of mature fruits, but Chen et al.[24] suggested that the application of abscission chemical agents should be avoided to make sure the safety of products and environmental conservation. Therefore, it's unsuitable to widely use in practical for mechanical fruits harvesting.

Shaking rods of the canopy shaker are responsible for energy transfer from the shaking mechanism to branches of the tree canopy. This transfer depends on the characteristics of the shaking rods which strike tree canopy directly. Most researchers focus on the shaking frequency and amplitude as the main factors affecting the tree damage and fruit removal, but there are few studies on the influence of the shaking rods. Gupta et al.[25] found that the optimized tine configuration of solid rod produced a prominent reduction in tree damage employing numerical-based design optimization when shaking the bottom, middle and top section of the tree canopy with different frequencies and amplitudes. Besides, Liu et al.[26] studied how the vibrational acceleration spreads along the shaken branch using three different tines. Their results showed that the vibration was spreading from shaking spot to the stem and obviously increased. However, the real canopy shaker strikes the tree canopy using a series of shaking rods but not a single tine. Therefore, it is essential to study the performance of the integrated shaking rods of canopy shaker including property and vibration performance which may affect tree damage and fruit harvesting efficiency.

This research mainly focuses on selecting and evaluating the influence of shaking rods with different materials or shapes on tree damage and fruit removal. The goal of this work was to assess the tree damage level and fruit removal percentage caused by shaking rods with different properties through experimental tests. Specific objectives were as follows: (1) to analyze the bending properties of the shaking rods with different material or shapes; (2) to compare the shaking performance of the selected shaking rods; (3) to evaluate the effect of different shaking rods on tree damage level and fruit removal percentage.

2 Materials and methods

2.1 Selected shaking rods

Material and shape are the two main features of the shaking rod for canopy shaker. Until now, straight rod and bow-shaped rod are the most commonly used shaking rods in canopy shaker. In order to study the effect of the material or shape of the shaking rods on tree damage and fruit detachment, the characteristics of three types of shaking rods were investigated. These selected shaking rods are shown in Figure 1. The rigid shaking rod (R_1) with the material of Polyvinyl Chloride (PVC) and flexible shaking rod (R_2 and R_3) with the material of Polyamide Nylon 12 (PA) were adopted for this study. On the other hand, the straight rod (R_2) and bow-shaped rod (R_3) with the same material of PA were employed to investigate the effect of shape of the shaking rod on tree damage and fruit removal. Therefore, three kinds of shaking rod were selected to evaluate the tree injury level and fruit detachment percentage. The physical properties of the selected shaking rods were listed in Table 1. Density, elastic modulus and flexural modulus were extracted from materials handbook[27]. The length and diameter of the shaking rods were measured using meter ruler and Vernier caliper with resolution of 0.1 mm, respectively.

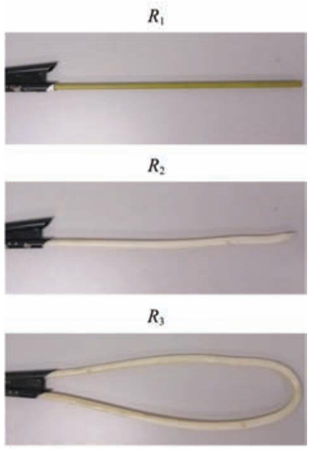


Figure 1 Three kinds of shaking rods: rigid shaking rod (R_1); flexible shaking rod (R_2); and bow-shaped shaking rod (R_3)

Table 1 Physical properties of the selected shaking rods

Name	Material	Length /mm	Diameter /mm	Density /kg·m^{-3}	Elastic modulus/GPa
R_1	Polyvinyl Chloride (PVC)	860	19.3	1550	2.7
R_2	Polyamide Nylon 12 (PA)	860	25.8	1010	2.0
R_3	Polyamide Nylon 12 (PA)	860	25.8	1010	2.0

2.2 Bending deformation analysis

2.2.1 Statics analysis

Shaking rod of the canopy shaker produces bending deformation under the stress of reactive force when striking the branch of tree canopy. So it is essential to investigate the bending properties of the shaking rods with different materials or shapes. In this study, the selected three kinds of shaking rods with the same length of 860 mm were equivalent to cantilever beam. According to the theory of material mechanics[28], deflection (w) and intersection angle (θ) are the foremost parameters for expressing the bending deformation of the cantilever beam. However, in this study, the intersection angle was not the required factor for the bending deformation of the bow-shaped rod. Therefore, deformation test was conducted to investigate and evaluate the bending deflection of the shaking rods with different material and shape as shown in Figure 2. The axial line of cantilever before bending deformation was set as x axis. And the direction of deflection defined as y axis was perpendicular to x axis. The one end of the shaking rod was fixed on test bench by clamping device. Three points with length of 300 mm, 500 mm and 700 mm from the clamping position were selected. Deformation tests on these three points were carried out 10 times, respectively. The imposed external force was increased gradually and measured by a calibrated digital force gage (model FDIX Series, Wagner instruments, Greenwich, CT, USA) with accuracy of 0.2 N and range of 250 N. And the deflection was measured by a meter ruler with accuracy of 0.1 mm. Flexural index was defined to represent the bending strength calculated by the following Equation (1). Namely, higher flexural index means that the shaking rod is more difficult to produce bending deformation.

$$F_{index} = \frac{F_i}{w_i}, \ i = 1, 2, \text{ and } 3 \tag{1}$$

where, F_{index} is the flexural index of the shaking rod, N/mm; F_i is the external force, N; and w_i is the deflection of shaking rod under F_i, mm.

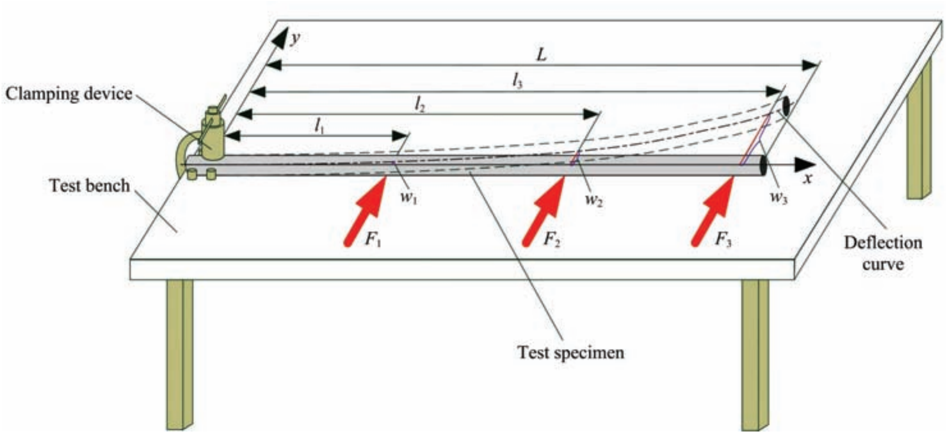


Figure 2 Schematic diagram of the bending deformation test under an external force

2.2.2 Dynamic vibration analysis

Shaking rod of the canopy shaker is the key unit transferring vibration energy from the shaking mechanism to the tree canopy for fruit detachment. In this study, this vibration procedure is a dynamic processing when the shaking rod strikes the tree canopy. Besides, the shaking rod also produces elastic deformation because of the inertia force when the shaking rod arrives at the extreme position. Figure 3 showed the schematic diagram of the dynamic vibration of the shaking rod. The sector area with two extreme positions of OP_1 and OP_2 was the moving range of the shaking rod without elastic deformation. The dashed line OP_3 and OP_4 represented the extreme position when the shaking rod produced elastic deformation. The variable angular velocity and acceleration of the shaking rod were represented with $w(t)$ and $a(t)$, respectively. Based on the Newton's Second Law of Motion[30], the inertia force of the barycenter point (M) could be displayed with a vector Equation (2). Obviously, the vibration strength of the shaking rod is significantly associated with the variable angular acceleration.

$$\overrightarrow{F_r} = m \cdot \overrightarrow{a(t)} \tag{2}$$

where, F_r is the instantaneous resultant force along with the shaking direction, N; m is the mass of the shaking rod, kg; $a(t)$ is the variable acceleration of the shaking rod, m/s^2.

In addition, the elastic deformation of the shaking rod was produced by the inertia force. The maximum deflection at the barycenter point can be calculated by the following Equation (3) based on the theory of material mechanics[28]. It indicated that the deflection of the shaking rod was also related to the vibration acceleration and the flexural rigidity of the shaking rod.

$$d_{MN} = \pm\frac{5F_r l^3}{48EI} \tag{3}$$

where, d_{MN} is the deflection of the shaking rod represented with MN, as shown in Figure 3, mm; ± represents the opposite direction of the reciprocating vibration; l is the length of the shaking rod, mm; EI is the flexural rigidity of the shaking rod, N/mm^2.

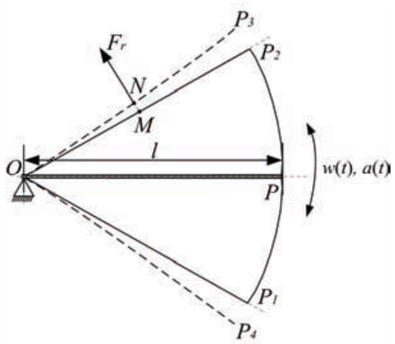
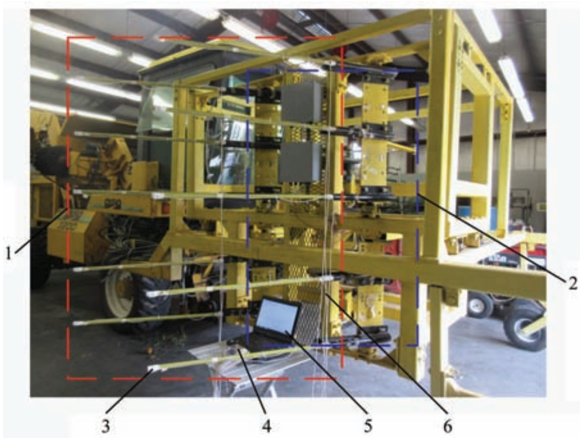


Figure 3 Schematic diagram of the dynamic vibration of the shaking rod

2.3 Shaking performance test

2.3.1 Experimental setup

Frequency and amplitude are the important parameters that need to be considered for evaluating the shaking performance of the shaking rod in canopy shaking. The above dynamic vibration analysis manifested that the acceleration of the shaking rod could significantly affect its shaking performance. Therefore, it is necessary to investigate the acceleration variation of the shaking rod during the dynamic vibration. In this study, the selected shaking rods were respectively mounted on a prototype of canopy shaker as presented in Figure 4. The hydraulic motor driving the shaking rod was operated with the same rotational speed of 160 r/min, measured by a Digital Hand-Tachometer (CDT-2000HD, Electromatic Equipment Co., Cedarhurst, NY, USA) with the accuracy of 0.02% and a resolution of 0.01 r/min. The vibration performance tests of the selected shaking rods were carried out using an acceleration measurement system to obtain the frequency and acceleration amplitude variation. In order to measure the acceleration variation and evaluate the shaking system accurately, 10 triple-axis accelerometers were separately aligned and attached to the end of 10 shaking rods as shown in Figure 4. Afterwards, the acceleration data was processed to acquire the frequency and amplitude variation through analyzing the algorithm using Matlab Software. Finally, the mean values and standard deviations (SD) of the frequency and acceleration amplitude were obtained by statistical analysis. Additionally, the shaking displacement was mainly determined by the designed structure which can be calculated by the mechanism parameters, but it is also affected by the elastic characteristics of the shaking rod, which was not practical to measure in this study.



1. Shaking rod 2. Vibration unit 3. Accelerometer 4. Data logger 5. Laptop 6. Wires

Figure 4 Vibration performance test of the shaking rod

2.3.2 Acceleration measurement system

An acceleration acquisition system with multi-channel accelerometers and data logger was specifically developed to measure and record the accelerations required for this study. As shown in Figure 5, the measurement system consists of several ultra-low-power high-performance triple-axis accelerometers with 10-bit precision (model LIS3DH, Adafruit, NY, USA), data logger with an eight-bit microcontroller (model ATmega32U4, Atmel Corporation, San Jose, CA, USA), a 12-microelectro mechanical systems digital output motion sensor and two eight-channels I^2C multiplexers (model TCA9548A, Adafruit), and an universal serial bus (USB) cable (AWM 2725) connected to a laptop computer (model ThinkPad, Intel(R) Core™ i7 CPU processor, Lenovo, China). The microcontroller was programmed to sweep and collect all data from all connected accelerometers and transfer them immediately to the connected computer via USB cable. The CoolTerm terminal software was used to log data from the USB cable with a baud rate of 9600 bits per second and record them in a file on the computer for further process and analysis. In order to reduce the sampling time, the microcontroller code only did the task of logging data with an average sampling time of 60 ms.

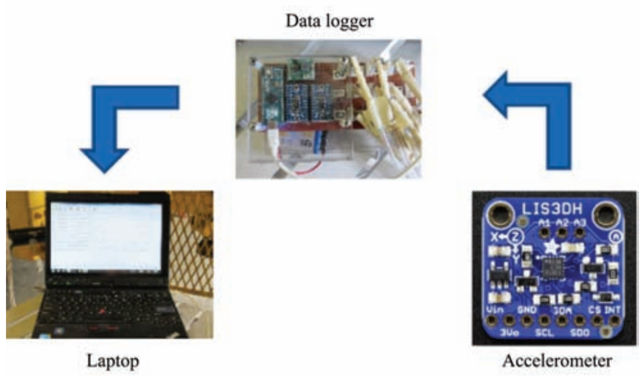


Figure 5 Acceleration measurement system

2.3.3 Frequency analysis

The measured data of acceleration was stored in a database for acceleration processing by a higher-speed processor on the computer using Matlab Software (R2010b, Version 7.11.0.584, Natick, MA, USA). The resultant acceleration value, which was the vector sum of the three axis values on each accelerometer[29], was calculated to analyze the vibration performance using the equation as follow:

$$A_{ccr} = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{4}$$

where, A_{ccr} is the resultant acceleration value, m/s^2; a_x, a_y and a_z are the instantaneous acceleration values of the x-axis, y-axis and z-axis for each acceleration, m/s^2.

Algorithm was also developed for processing data in MATLAB environment, including acceleration peak, frequency counter, data points, fitting and statistical data analysis. Figure 6 shows the computational method of the vibration frequency analysis through an interception fragment of acceleration variation. The algorithm of the frequency analysis was calculated by the following formulas:

$$\sum_{i=1}^{n} T_i = t_n = n\overline{T_i} \tag{5}$$

$$\overline{f} = \frac{1}{\overline{T_i}} = \frac{n}{t_n} \tag{6}$$

where, T_i is the time as the period of the adjacent peak, s; t_n is the total time of the acceleration duration, s; $\overline{f}$ is the mean values of frequency, Hz. Equation (6) was deduced by Equation (5).

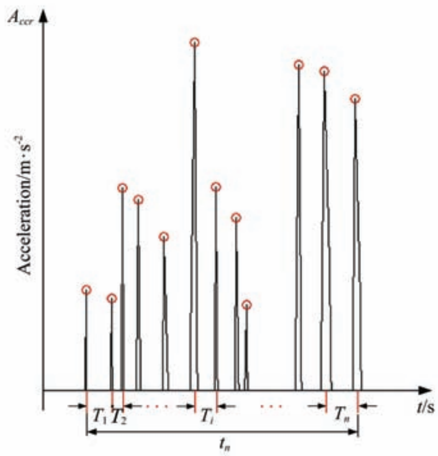


Figure 6 Frequency analysis through acceleration variation

2.4 Field trial evaluation

2.4.1 Field test preparation

The study area for this field test is located in an orchard of Citrus Research & Education Center in Lake Alfred, Florida, United States. Field tests were conducted using the selected shaking rods mounted on a prototype of canopy shaker as shown in Figure 7. The variety of the citrus trees used in this study was 'Valencia' orange. The trees were planted with a 6 m row spacing and a 4-m in-row tree spacing in 2005. Before harvesting, all the trash under the tree canopies was removed by raking to avoid any error in measuring the fruit removal and tree damage rate. The field trial was carried out on March 15, 2017.

Figure 7 Field test of the selected shaking rod mounted on a canopy shaker

2.4.2 Fruit removal and tree damage evaluation

Based on the purpose of this study, the effect of different shaking rods on fruit removal and tree damage was assessed by evaluating the fruit detachment rate and tree damage level. In this study, three sets of field tests were conducted on three rows employing different shaking rods. The initial motor rotating speed was set at 160 r/min based on the vibration performance test of the shaking system. The selected 10 twelve-year-old trees in each row could be harvested continuously. Each test harvested 10 trees under the same hydraulic motor speed, namely the same shaking frequency. After the end of each canopy shaking operation on the both sides of each row, the total detached oranges and dropped fresh debris were collected and weighted for each tree, respectively. Also, all the un-detached fruits on the tree were manually picked and weighed. The fruit removal percentage and tree damage rate were calculated by Equations (7) and (8), respectively.

$$FRP = \frac{M_{do}}{M_{do} + M_{uo}} \times 100\% \quad (7)$$

$$TDR = \frac{M_{dd}}{M_{dd} + M_{do}} \times 100\% \quad (8)$$

where, *FRP* is the fruit removal percentage, %; *TDR* is the tree damage rate, %; M_{do} is the mass of the detached oranges, kg; M_{uo} is the mass of the undetached oranges on the tree, kg; and M_{dd} is the mass of the dropped debris, kg.

3 Results and discussion

3.1 Property analysis of the shaking rods

Bending deformation test was conducted to evaluate the deformation extent of the selected shaking rods. Table 2 showed the experimental results of the flexural index which was defined to represent the bending strength. The mean values and standard deviations (SD) with a significant difference manifested that the flexural index of R_1 was much more than that of R_2 and R_3. It means that R_1 with the material of PVC is harder to produce bending deformation. In addition, the flexural index of the shaking rod R_2 and R_3 with the same material but different shape is similar. It indicated that the material of the shaking rod is the most significant factor determining the bending deformation. Besides, there was a similar tendency that the position closed to the free end of the shaking rod needed less external force to make bending deformation in accordance with the mechanics of materials[28]. In addition, the dynamic vibration analysis indicated that the vibration strength and elastic deflection of the shaking rod was significantly associated with the variable angular acceleration.

Table 2 Flexural index of the selected shaking rods

No.	F_{index} /N·mm^{-1}								
	Rigid shaking rod (R_1)			Flexible shaking rod (R_2)			Bow-shaped shaking rod (R_3)		
	l_1 (300 mm)	l_2 (500 mm)	l_3 (700 mm)	l_1 (300 mm)	l_2 (500 mm)	l_3 (700 mm)	l_1 (300 mm)	l_2 (500 mm)	l_3 (700 mm)
1	33.93	5.20	3.29	2.68	0.70	0.21	5.18	1.62	0.95
2	34.00	5.16	2.82	3.77	0.60	0.21	4.62	1.61	0.74
3	36.71	5.68	2.93	3.47	0.69	0.23	4.05	1.40	0.84
4	39.21	5.90	2.96	3.49	0.71	0.24	4.04	1.43	0.85
5	38.59	6.01	2.89	3.40	0.68	0.24	4.06	1.43	0.80
6	33.51	6.21	2.83	3.40	0.69	0.23	4.00	1.33	0.80
7	30.00	6.19	2.96	3.40	0.69	0.24	3.94	1.32	0.80
8	28.39	5.98	2.93	3.40	0.70	0.23	4.06	1.31	0.78
9	26.95	6.18	2.84	3.50	0.70	0.24	4.20	1.32	0.78
10	25.32	5.78	2.82	3.37	0.70	0.24	4.27	1.33	0.78
Mean	32.66	5.83	2.93	3.39	0.69	0.23	4.24	1.41	0.81
SD	4.59	0.36	0.13	0.26	0.03	0.01	0.36	0.11	0.05

3.2 Vibration performance of the selected shaking rods

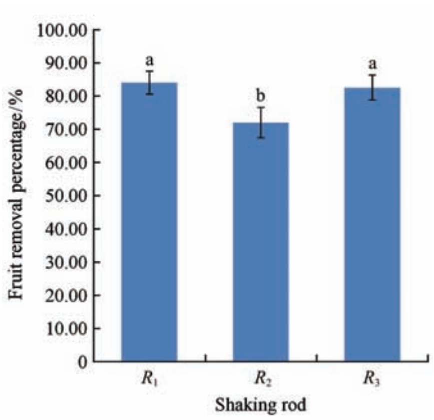
After analyzing the bending deformation properties of the selected shaking rods with static and dynamic vibration analysis, vibration performance tests using acceleration measurement system were conducted before field trial. Shaking frequency was obtained by analyzing the acceleration data. The performance parameters are presented in Table 3. It can be observed that the selected shaking rods obtain a similar frequency range from 1.7 Hz to 6.2 Hz driven by the same hydraulic motor speed of 160 r/min. These results agree with the recommendation that canopy shaker operates at an appropriate frequency range from 2 Hz to 6 Hz for citrus harvesting which has been reported by Savary et al.[11], but the mean values of the shaking frequency are different. It is clear that R_2 obtained a lower shaking frequency of 4.3 Hz than the other two shaking rods with a similar frequency around 4.8 Hz. On the other hand, R_1 and R_2 acquired the largest and lowest vibration acceleration, respectively. It indicated that R_1 with the material of PVC could produce stronger vibration with higher acceleration. Compared to the similar frequency range, the difference of the shaking frequency and peak acceleration was most likely caused by the bending deformation of the selected shaking rods. It seems that the difference of the flexural index also reflects the variable trend of the shaking frequency and acceleration of the shaking rod.

Table 3 Performance test of the selected shaking rods (Hydraulic motor speed = 160 r/min)

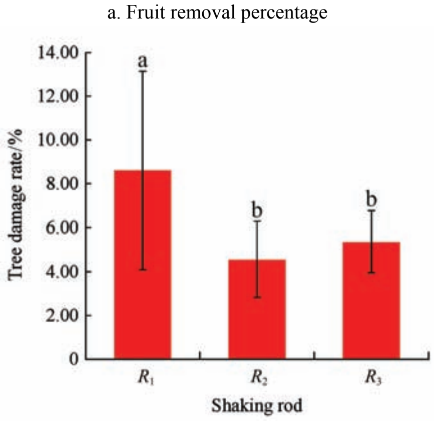
Parameters	Shaking rods		
	R_1	R_2	R_3
Frequency range/Hz	1.7-6.1	1.8-5.9	1.9-6.2
Shaking frequency/Hz	4.8±0.5	4.3±0.7	4.7±0.4
Acceleration amplitude/$m \cdot s^{-2}$	31.4±2.1	26.7±1.4	28.6±2.8

3.3 Fruit removal and tree damage evaluation

In this study, fruit removal rate and tree damage level are the two key concerns used to evaluate the advantages and disadvantages of the selected shaking rods for citrus canopy shaking. Figure 8 shows the results of the fruit removal percentage and tree damage rate generated by the selected shaking rods through the field tests. For all of the fruit removal percentages and tree damage rates, there was a significant difference that R_1 could remove more fruits but also produce higher tree damage rate of over 13% with large standard deviation. Compared to R_2 with lower fruit removal rate of 72.03%, R_1 and R_3 can get similar high fruit removal percentage up to 84.08% and 82.6%, respectively. However, R_3 produces a fewer tree damage rate of 5.36%. According to the performance test results of the selected shaking rods shown in Table 3, it demonstrates that the higher shaking frequency and acceleration of the shaking rod probably produce more fruit removal but also higher tree damage rate simultaneously, which is the similar conclusion reported by Hong et al.[13]



a. Fruit removal percentage



b. Tree damage rate

Note: Different letters indicate significant differences of the fruit removal percentage and tree damage rate produced by different shaking rods.

Figure 8 Mean values and standard deviations of the fruit removal percentage and tree damage rate

From the view of mechanics based on Newton's Second Law of Motion[30], R_1 with higher acceleration can produce larger impact force striking the tree canopy. The larger impact force probably causes more serious tree damage, especially breaking off the stems, branches and leaves. As the reason for the fruit damage during mechanical harvesting reported by Castro-Garcia et al.[10], tree damage was also correlated with vibration acceleration and frequency produced by shaking rods of canopy shaker. This consequence is consistent with the results of previous studies that high frequencies and amplitude could produce more debris for citrus mechanical harvesting[3,12,13].

Combining the advantages and drawbacks of both fruit removal percentage and tree damage rate, it was clear that R_3 acquired a lower tree damage level than R_1 while both of them obtained a similar fruit removal percentage. It indicated that the flexible bow-shaped shaking rod was a compromise choice to achieve acceptable fruit removal percentage and a lower tree damage level. Therefore, flexible bow-shaped shaking rod has a better widespread performance to maintain higher fruit removal percentage while producing less tree damage. It demonstrates that selection of the shaking rod for canopy shaker is an imperative aspect to reduce tree damage.

4 Conclusions

In this study, three kinds of shaking rods with different materials or shapes were selected and evaluated through laboratory experiments and field tests. The major achievements of this research can be summarized as follows:

(1) The rigid shaking rod with the material of PVC is harder to produce flexural deformation than that of other two shaking rods with the material of PA. Meanwhile the bow-shaped shaking rod has higher bending strength than the straight flexible shaking rod. And the vibration strength and elastic deflection of the shaking rod are significantly associated with the variable acceleration.

(2) The rigid shaking rod could produce stronger vibration with higher shaking frequency of 4.8 Hz and peak acceleration of 31.4 m/s^2 than the other flexible shaking rod under the same operated hydraulic motor speed of 160 r/min.

(3) The bow-shaped shaking rod, compared to the straight rigid and flexible shaking rod, has better widespread performance to produce lower tree damage of 5.36% and achieve higher fruit removal percentage up to 82.6% as well.

This research could provide a reference to the application of shaking rods for canopy shaker. It also demonstrates that the selection of shaking rods is an essential aspect to reduce tree damage and obtain more fruits removal. Furthermore, the tree damage mechanism of canopy shaking should be investigated in the future work to obtain optimized parameters of the shaking rod for reducing tree damage and detaching more fruits.

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