Article

Citrus Fruit Movement Assessment Related to Fruit Damage during Harvesting with an Experimental Low-Frequency–High-Amplitude Device

Coral Ortiz [1,*] , Antonio Torregrosa [1] and Sergio Castro-García [2]

1   Departamento de Ingeniería Rural y Agroalimentaria, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain; torregro@dmta.upv.es
2   Escuela Técnica Superior de Ingeniería Agronómica y de Montes, Campus de Rabanales, Universidad de Córdoba, Ed Leonardo da Vinci, Ctra N-IVa, km 396, 14071 Córdoba, Spain; ir1casgs@uco.es
*   Correspondence: cortiz@dmta.upv.es

Abstract: The profitability of fresh citrus crops outlines the possibility of using mechanical systems to reduce the high cost of the manual harvesting operation. In this line, an experimental light shaker with low frequency and high amplitude and a hydraulic arm was developed. This device had been successfully used for harvesting ornamental citrus trees. In previous studies, it was proven that the removal percentage was adequate, but the percentage of slightly damaged fruit increased compared to a traditional fruit trunk shaker. Visualizing the fruit movements in high-speed video recording images during harvesting, a higher impact level was observed due to the higher amplitude. The aim of this study was to analyze the fruit movement during the vibration with the experimental shaker compared to the movement when vibrating with an orchard tractor mounted trunk shaker related to the increase of slightly damaged fruit when using the experimental shaker. Fruit movement parameters (fruit distance, fruit displacement, speed and acceleration) when using the two harvesting systems (experimental shaker and trunk shaker) were compared analyzing the high-speed video recordings. Results showed that the higher vibration amplitude produced a maximum distance experienced by the fruits (maximum displacement of 0.135 m with the experimental shaker compared to 0.078 m with the trunk shaker) that could cause a higher damage level (74% of slightly damaged fruits using the experiemntal shaker compared to 14% using the trunk shaker).

Keywords: citrus; mechanical harvest; movement; image analysis; vibration

1. Introduction

In Valencia (Spain), citrus fruit are mostly destined for the fresh fruits market and are harvested by hand. The mechanical harvesting technology is being developed in fruit and nut crops with the aim of reducing the cost of harvesting and the limitations of available labor [1]. Canopy shaker and trunk shaker systems are presented as technologies able to increase labour productivity by up to 15-fold and reduce costs by up to 50% [2]. Previous studies showed the effectiveness of vibration systems for mechanical citrus harvesting [3,4]. Canopy shaking systems have been developed in citrus for industrial transformation, where damage to the fruit is less important. These systems are under development and have a promising future [5,6]. However, the fruit damages produced are crucial for the fresh market. Mechanical harvesting systems have been studied to reduce the high costs of manual harvesting, but the damages produced to the fruit are crucial. Previous studies showed the effectiveness of vibration systems for mechanical citrus harvesting [7,8]. Vibrational limb and trunk shaking systems have been tested for mechanical citrus harvesting [3,9–12]. Trunk shakers can be used to harvest citrus fruits; frequencies around 15 to 25 Hz and amplitudes around 0.02 m have shown promising results. The removal percentages depend on the harvesting device, the variety and the structure of the tree. In the case of

citrus fruits for fresh market, [13] showed that trunk shakers could reach a harvesting efficiency of 70%, while hand-held shakers could reach a harvesting efficiency value of 76% on branches. In both cases, proper structure of the tree and its branches could increase harvesting efficiency. Subsequently, [14] managed to increase the average harvesting efficiency with trunk shakers, with average values of 70–85%, with acceptable levels of defoliation and with fruit retaining its calyx. However, limiting damage to fruit destined for the fresh market is an issue of concern for the implementation of mechanical harvesting. In order to gather more information about fruit detachment principles, image analysis was used with a high-speed commercial camera to allow the recognition of olive fruits, obtaining fruit movement parameters such as velocity, acceleration, and stalk torsion [15]. The movement of the fruit as a mathematical pendulum was described by [16] during branch vibrations using a theoretical non-linear numerical mathematical model. Laboratory studies showed the possibility of detaching citrus fruit using lower frequencies and higher strokes to reduce leaf losses [7]. The mechanical citrus harvesting parameters (frequency, amplitude and duration) to ensure maximum removal efficiency were determined by [7] using a laboratory experimental device. The results were compared to those found in field tests. The possibility of reducing the frequencies and increasing the amplitudes to achieve an optimal mechanical citrus harvest was confirmed (amplitude values higher than 0.06 m and frequencies around 5 Hz). The problem of the increase of leaf and stem debris in citrus mechanical harvesting was addressed [17]. Lower frequencies and higher amplitudes have proven to reduce leaf losses in laboratory studies [18]. However, conventional trunk shakers are not able to increase the amplitude according to the laboratory proposed values. A cushioned and elevated canvas on the ground has been proven to reduce the collecting damages [19]. Previous studies addressed the vibratory behavior of citrus fruits using high-speed cameras to assess the parameters involved in fruit detachment during vibratory mechanical harvesting [13]. They used vibrations with strokes from 60 to 180 mm and frequencies from 3 to 18 Hz.

A light-weight experimental shaker was developed and successfully tested to harvest ornamental citrus trees [20]. The frequency used was between 4 and 6 Hz, and the stroke was 0.06 m. The gripper was capable of grasping the low diameter trunk to be shaken. Low-frequency commercially available canopy shakers, that work with lower frequency, can not be used in Valencia (Spain) citrus orchards due to the big size of the machines and the excessive damage to the fresh market fruit. Then, the light-weight experimental shaker suscesfully used in ornamental trees was improved to harvest fresh citrus orchards, gripping the main branches [21]. Elevated canvases were employed to collect the fruit without damage. Severe damages were very low (2% of the detached fruits). However, fruit light damages on the tree during the high-amplitude vibration seemed to be relevant, 78% of slightly damaged fruits when using the experimental shaker compared to 14% when using a trunk shaker [22]. The higher damage percentage could be due to the fact that some of the fruits are being rubbed against the branches and other fruits during the vibration. The objective of this study was to analyze the fruit movement during the vibration with the experimental shaker, compared to the movement when vibrating with an orchard tractor-mounted trunk shaker, related to the previously proven increase of slightly damaged fruit when using the experimental shaker.

2. Materials and Methods

The mechanised harvesting trials were carried out in an experimental plantation of ANECOOP located in Museros (Valencia, Spain). The trees ('Caracara' variety) were in good health and nutritional condition, assessed by the agriculture cooperative technician, with no particular nutritional deficiencies and appropriate growth and characteristics according to the variety and age. Two harvesting systems were used to detach the fruit. The first was a commercial trunk shaker (CTS) and the second was an experimental light-weight shaker (ELWS), as shown in Figure 1. The CTS was tractor-driven (66 kW four-wheel drive model) and consisted of a vibrating head mounted on an articulated extension arm

coupled to the tractor's front three-point hitch with two clamping arms with a mass of 730 kg. The vibration was driven by the tractor's power take-off via two hydraulic oil pumps. The shaker drove an eccentric mass of 16 kg, with an eccentricity of 0.13 m, producing an orbital vibration (Topavi light shaker, Maquinaria Agrícola Garrido S.L. (Topavi), Autol, Spain, www.topavi.es). This CTS allows the regulation of the vibration generated and can be used in mechanized citrus harvesting [14]. The vibration produced was regulated with a peak-to-peak amplitude of 0.06 m. The ELWS was designed for low-frequency and high-amplitude vibration of citrus fruits [22]. The ELWS consists of a disc that is driven by a hydraulic motor; therefore, by modifying the hydraulic flow, the vibration frequency can be modified. A rod is connected to the disk. The disc and connecting rod assembly transforms the rotating movement of the hydraulic motor into a reciprocating linear movement. The connecting rod can be attached to the disc through holes located at different distances from the center, with which the stroke can be modified. The opposite end of the rod is connected to a slider for pure reciprocating linear motion. The slider is connected to an arm, at the end of which is the clamp with cushioned fingers, which holds the branch (Figure 1). The vibration produced was unidirectional, applied to the main branches of the tree, and in a wide grip with 60 mm thick rubber. ELWS was driven by a pedestrian hydraulic tractor (Hinowa, Nogara, VR, Italy; Hinowa.com) 'Hinowa' model HS 11000 provided with a fork elevator. ELWS was powered by the hydraulic system of a tractor (Lamborghini Plus 990 F) with a flow rate of 21 L/min at 100 bar.
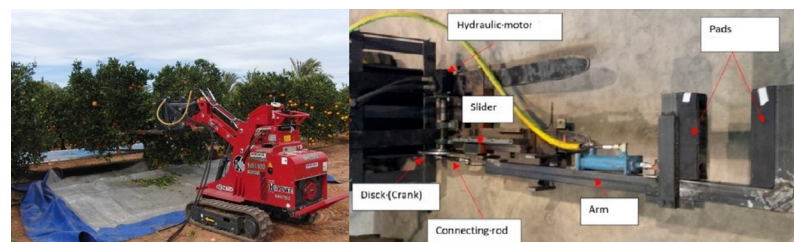

Figure 1. Experimental light-weight shaker vibrating a tree (**left**) and experimental light-weight shaker elements (**right**).

The trees were vibrated at a height of 0.2 m from the ground with the CTS. With the ELWS, the main branches of the tree were selected and vibrated. Each harvesting system was used for the time necessary to detach the fruit susceptible to be detached by the vibration. The vibration process was recorded with a high-speed camera, perpendicular to the canopy stage zone at 300 fps (CASIO model EXF1).

Fifty fruits were manually collected in order to measure fruit quality parameters (retention force, mass, diameters, sugar content and totral acidity). Retention force was measured with a digital dynamometer (Advanced Force Gauge 500 N, Mecmesin, Horsham, UK) with a cylindrical structure that allowed to pull the fruit in the horizontal direction. The fruit collected using the dynamometer were transported to the laboratory the same day where they were tested. Mass was measured with an electronic balance (Mettler Toledo AL104 electronic balance, Rondo Tower, Switzerland). Diameters were registered using a digital caliper electronic vernier scale (Holite Electrical Co., Ningbo, China). Soluble solid content was determined with a digital refractometer (Atago model PAL-3; Atago Co., Tokyo, Japan). Tritatable acidity was measuring with an automatic titrator (Mettler Toledo T50, Rondo Tower, Switzerland). The fruits had an average retention force of 53.5 N (SD $\pm$ 20.1), a mass of 187.1 g (SD $\pm$ 50.2), and diameters of 72.25 mm (SD $\pm$ 6.5) and 66.1 mm (SD $\pm$ 6.5). The maturity index was 12.7, with an average sugar content of 14.2 Brix and an average titratable acidity of 11.16 g/L.

Six trees from every harvesting system were vibrated and the operation was recorded. From these trees, one tree from each harvesting system was selected to assess fruit movement, considering the tree structure, the quality of the high-speed video recordings and the position of the fruits (mostly in the xy plane, perpendicular to the video recording direction). From these selected trees, five fruits were chosen to be studied according to

the position of the fruit and the lack of leaves around the movement covering the image. Then, from the different video recordings, two clear high-speed videos from two typical trees were selected, one vibrated by the trunk shaker and one with the experimental shaker (Figure 2). From each video, five fruits whose movement was clear and mostly in the xy plane (perpendicular to the video recording direction) were chosen to be studied. An electronic sphere (Tuberlog PTR 200, Landtechnik) was used to assess the impact values during vibration. The actual frequencies were measured using a triaxial accelerometer and recorder (Gulf Coast Data Concepts, LLC, Waveland, MS, USA; http://www.gcdataconcepts.com) that recorded the vibrations at 400 Hz and with high-speed video recording, counting cycle time (with a camera Casio EX-F1, at a rate of 300 images per second, was used to acquire the images with a size of 584 × 312 pixels and a resolution of 3.65 mm/pixel). The image analysis software ImageJ (https://imagej.nih.gov/ij/) was used to track the position of the fruit during the vibration using a semi-manual process through the menu "Tracing tool/ Analyze/Measure". The image analysis software was used to identify the citrus fruit from the rest of the image. Every four photograms, the center of the analyzed fruit was manually marked and the coordinates (x_i, y_i) registered. The trajectory of the fruit was registered with the coordinate change according to time. Then, fruit distance (*d*), fruit displacement (*de*), speed (*v*), and acceleration (*a*) were calculated. The distance of the fruit related to the initial position (*d*, fruit distance (m)) was calculated according to Equation (1), being (x_i, y_i) the position of the fruit at time i and (x_0, y_0) the position of the fruit at the initial time before vibrating.

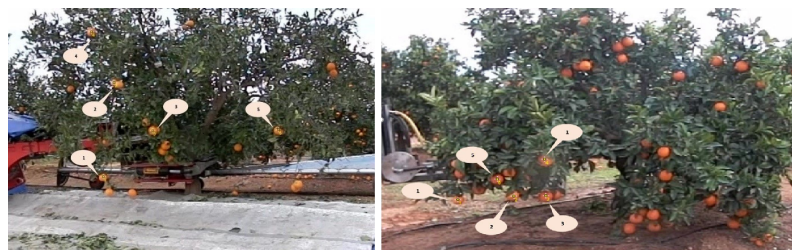$$d^2 = [(x_i - x_0)^2 + (y_i - y_0)^2] \tag{1}$$

Figure 2. Tested trees and selected fruit vibrated with a commercial trunk shaker (**left**) and an experimental light-weight shaker (**right**).

The relative displacement of the fruit (de, fruit displacement (m)) was calculated according to Equation (2), being (x_{i+1}, y_{i+1}) and (x_i, y_i) the positions of the fruit at two consecutive times.

$$de^2 = [(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2] \tag{2}$$

The speed was calculated according to Equation (3).

$$v = (de_{i+1} - de_i)/(t_{i+1} - t_i) \tag{3}$$

The acceleration was calculated according to Equation (4).

$$a = (v_{i+1} - v_i)/(t_{i+1} - t_i) \tag{4}$$

Analysis of variance (ANOVA) using Statgraphics Centurion 18 Software, version 18.1.13 (Statgraphics Technologies, Inc. The Plains, VA, USA) was applied to evaluate the differences among the samples. The effect of the factor harvesting system on the variables velocity and acceleration values measured on fruit during the harvesting process and fruit displacement related to the initial fruit position was addressed. The LSD Fisher (less significant difference) was used for mean separation at $p < 0.05$. Although the data did not follow homocedastiticity and normal distribution of residuals, the results of ANOVA were considered valid due to the robustness of the ANOVA. A step-by-step discriminant

analysis was also developed to classify the fruit between the two groups (vibrated by the experimental shaker and vibrated by the trunk shaker) according to the registered and calculated variables.

3. Results

3.1. Vibration Frequency of the Fruit

The tested mechanised harvesting systems showed different vibration frequency values. The CTS vibration frequency was between 14 and 18 Hz and with an accumulated vibrating time around 8 s. On the other hand, ELWS worked with a lower frequency than CTS, with an average frequency value of 5.7 Hz, values between 5 and 6 Hz, and a vibrating time of 30 s. Figure 3 shows a sample of the branch and fruit vibration using both harvesting systems. Due to the difficulties related to establishing a sinusoidal curve fitting of the fruit movement, a moving average of 2 values was used. Fruit vibrated by ELWS received a frequency two to three times lower than the fruit vibrated by the trunk shaker, receiving fewer vibrating cycles per second. However, considering that the vibrating time was four times higher in the case of the ELWS than to CTS, the fruit vibrated using this device experienced more vibrating cycles.
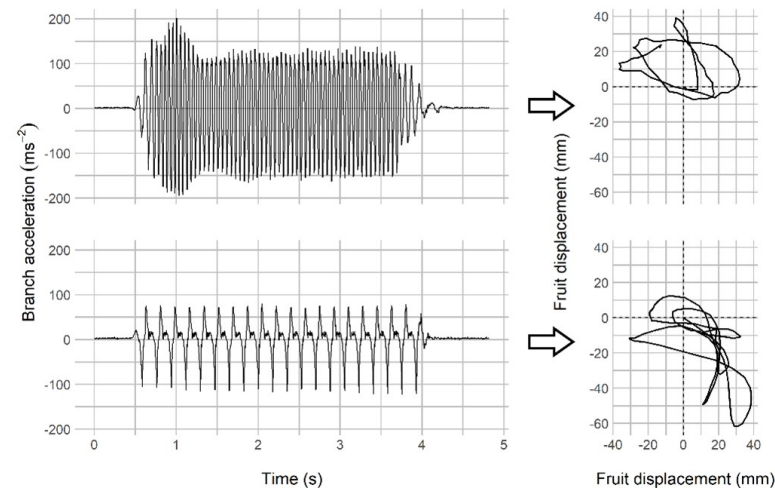

Figure 3. Examples of branch acceleration (**left**) and fruit displacement (**right**) during mechanical harvesting with commercial trunk shaker (**top**) and experimental light-weight shaker (**bottom**). The data shown are measured on different fruits and branches and limited vibration time.

3.2. Acceleration of the Fruit

The determination of velocity and acceleration was limited by the measurement of the displacement in the projection of the plane perpendicular to the recording and by the accurate determination of the centroid of the fruit. The measurement of the fruit displacement in a small time interval (0.003 s), combined with its averaging in root mean square (RMS) value, made it possible to estimate the values of velocity and acceleration. As expected, the acceleration and velocity, maximum and root mean square values were significantly higher in the fruit vibrated by CTS (with a higher frequency value) than in the fruit vibrated by ELWS (Table 1). RMS acceleration registered in the fruits vibrated by the trunk shaker were around twice the acceleration registered in the fruits vibrated by the experimental shaker.

Table 1. Velocity and acceleration values measured on fruit during the harvesting process with a commercial trunk shaker (CTS) and experimental light-weight shaker (ELWS) showed as root mean square (RMS) and maximum values (values shown are mean, with standard deviation in brackets. The same letter in the same column is not significantly different (Tukey post hoc test, $p < 0.05$)).

	Fruit Velocity (m s^{-1})		Fruit Acceleration (m s^{-2})	
Device	**RMS**	**Maximum**	**RMS**	**Maximum**
CTS	0.35 (0.06) b	1.14 (0.22) a	22.31 (4.53) a	75.87 (24.25) b
ELWS	0.22 (0.06) a	0.78 (0.28) a	11.36 (3.40) a	43.54 (17.08) a

3.3. Displacement Related to the Initial Position

The fruit displacement related to the initial position (static before vibrating) was significantly higher in the case of the ELWS compared to the CTS in the horizontal axis (Table 2). This high displacement seems to be related to the high amplitude of the vibration using the ELWS. The displacement of the fruit related to the initial position before vibrating is significantly higher in the case of the fruit vibrated by the ELWS compared to the ones vibrated by the CTS ($p = 0.025$). This fact is also confirmed in the variables, absolute maximum distance of the fruit related to the initial position and the variables in both axes.

Table 2. Displacement values (mm), related to the fruit initial position, measured during the harvesting process with a commercial trunk shaker (CTS) and experimental light-weight shaker (ELWS) shown as average and absolute maximum distance in the horizontal and vertical axes (values shown are mean, with standard deviation in brackets. The same letter in the same row is not significantly different (Tukey post hoc test, $p < 0.05$)).

	Fruit Displacement (mm)		Max Fruit Displacement (mm)	
Device	**Average**	**Maximum**	**Horizontal Axis**	**Vertical Axis**
CTS	36.8 (14.8) b	78.0 (24.4) b	72.9 (23.9) b	49.8 (18.4) a
ELWS	62.0 (14.2) a	135.1 (44.8) a	111.1 (25.7) a	95.0 (57.7) a

3.4. Discriminant Analysis of the Fruit

Finally, in order to summarize the main results, a step-by-step discriminant analysis was developed to classify the fruit between the two groups (vibrated by the experimental shaker and vibrated by the trunk shaker), as shown in Figure 4. Only two variables were selected, RMS acceleration (m s^{-2}) and absolute maximum distance (m), obtaining 100% well-classified fruits. Fruits vibrated by the trunk shaker had a high RMS acceleration value (more than 16 m s^{-2}) and lower displacement from the initial point (lower than 0.12 m). However, fruit vibrated by the experimental shaker had a lower acceleration (lower than 16 m s^{-2}, in most of the cases lower than 12 m s^{-2}) and a higher displacement related to the initial position (between 0.09 and 0.2 m).
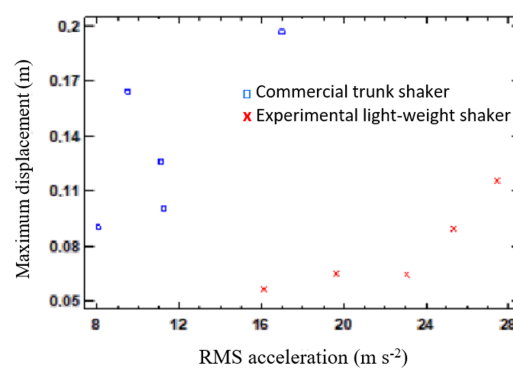

Figure 4. Dispersion diagram from the discriminant analysis to classify the citrus fruit between the two harvesting systems studied.

4. Discussion

Fruit damage caused by mechanised harvesting is usually more significant than that caused by manual harvesting [23]. The application of a forced vibration on the trunk (case of CTS) or on the branch (case of EWLS) causes the fruit movement. As a consequence, these fruits before their detachment have an initial velocity value in the canopy and can reach impacts of greater magnitude than what could be a natural fall or manual harvesting [8]. This study showed that fruit movement in the canopy is of a large magnitude, with maximum values in the range of 78 to 135.1 mm and dependent on the harvest device. These values facilitate fruit detachment but simultaneously increase fruit damage during picking. Due to the movement of the fruit during the mechanical detachment process, they could hit against other fruits, branches, picking structures or the ground [24]. However, these impacts can be reduced by using an elevated canvas or picking structures that intercept the fruits with cushioned surfaces [19]. Other authors suggested the possibility of tree training to limit canopy density to reduce fruit-branch damage, which causes up to 60% of fruit damage when using trunk vibrators [25].

During the mechanical harvesting process, the movement of the fruit causes stress on the stalk, which, together with material fatigue phenomena, leads to its detachment [18]. However, the area of fruit abscission differs depending on the harvesting system used. When using canopy shaker systems with reduced frequency values (4.5–5 Hz), the predominant zone of abscission (58.8%) is breakage in the peduncle [26]. However, with the use of trunk shakers, with higher vibration frequency (9–25 Hz), fruit with calyx with a portion of peduncle or even a portion of branch is reduced to 28% [13].

The fruit requires a vibration time for its abscission. During citrus harvesting with trunk shakers, the fruit removal percentage exhibited a logarithmic behavior with time, with most of the fruit detached in the first 2–3 s of vibration [7]. The results obtained have shown that the movement of the fruit in the tree canopy has been generated with high displacement in the case of ELWS, higher than CTS. This high displacement, together with low-frequency values have been shown to be the most effective combination for fruit detachment [18].

Vibration frequency has proved to be an important parameter in the harvesting operation. The trends in the development of harvesting systems are moving toward the application of specific vibration parameters on different parts of the tree to improve harvesting efficiency and reduce tree damage [27]. In fact, research applied to the fruiting branches of the same tree shows that there are differences in the values of their natural frequencies [28]. The regulation of each harvesting device was determined by the frequency variation, and based on the eccentricity and the mass used in the specific device, the rest of the vibration parameters were defined in the trunk or branch. Subsequently, the location of the fruits and their characteristics conditioned their response in terms of acceleration, velocity and displacement. Fruit vibrated by ELWS received a frequency two to three times lower than the fruit vibrated by the CTS. However, considering that the vibrating time was four to six times higher, the fruit vibrated by CTS experienced more vibrating cycles. The fruit detachment process is facilitated by using long peak displacements, which require fewer cycles to achieve detachment [18]. However, previous studies showed that these high displacements may cause slight damage when the fruit impacts nearby branches and fruit [21,22]. This fact could explain that more fruit are rubbed against the branches and other fruits during the vibration, and it would be responsible for the higher percentage of slightly damaged fruit registered in the case of the trees vibrated by ELWS compared to the trees vibrated by CTS.

The harvesting systems tested showed high fruit RMS acceleration values, being higher in CTS (22.31 m s^{-2}) compared to ELWS (11.36 m s^{-2}). These values were lower than those recorded by [8] when studying canopy shakers in citrus harvest for industry (frequency 4.1–4.9 Hz, and average values between 38.8 and 60.4 m s^{-2}). The use of higher frequency value allows to obtain higher acceleration values for the fruits. Working with citrus branches [6] obtained an overall vibrational acceleration value 1.85 times higher when vibrating at 5 than at 2.5 Hz.

Increasing the acceleration in the canopy when using vibrators leads to better harvesting efficiency, [17]. However, it also contributes to increase damage to other plant organs, such as shoots, leaves or flowers [29]. In a study on the effect of frequency and amplitude on citrus tree vibration, [1] showed that damage to tree branches can be reduced by 30% by using different combinations of frequency and displacement. The combination of frequency and displacement can be optimized to harvest different parts of the tree canopy and maintain high harvesting efficiency values with less damage to the branches. Acceleration in the canopy is influenced by the amplitude generated in the vibration applied. The possibility of performing vibration on main branches using ELWS has made it possible to reduce acceleration values in fruit to values significantly lower than CTS. Previous studies with CTS have shown how fruit drop is conditioned by the acceleration values. The significantly lower RMS acceleration in the case of the fruit vibrated by the ELWS could produce slightly damaged fruits (small cuts, rubbing and very small bruises) and not considerable damaged fruits (bruises and cut wounds).

5. Conclusions

No relevant results were found using the electronic sphere to measure the acceleration values of the fruits. However, image analysis of the high-speed videos has proven to be useful to assess fruit movement parameters. Frequency extracted from the displacement, speed, and acceleration curves of the experimental shaker showed fruit vibration frequencies between 5 and 6 Hz compared to 5.7 Hz measured with the accelerometer in the branch. Frequency extracted from the displacement, speed, and acceleration curves of the trunk shaker showed fruit vibration frequencies between 12 and 18 Hz in the case of fruit vibrated by the trunk shaker compared with frequencies around 19 Hz measured with the accelerometer located in the trunk. These differences in the registered frequencies could be due to the difficulties in the sinusoidal curve fitting of the fruit movement. The acceleration and speed, maximum and root mean square values were significantly higher in the fruit vibrated by the trunk shaker than in the fruits vibrated by the experimental shaker. Fruit acceleration with the trunk shaker was twice the acceleration with the experimental shaker. Fruit displacement related to the initial position was significantly higher in the case of the experimental shaker compared to the trunk shaker, especially in the OX axis. This high displacement seems to be related to the high amplitude of the vibration using the experimental shaker. This fact could explain the previous results showing that more fruit are rubbed against the branches and other fruits during the vibration, and it would be responsible for the higher percentage of slightly damaged fruit. The low amount of severe damages compared to light damages could be due to the lower acceleration in the case of the fruit vibrated using the experimental shaker. Further studies should be addressed to verify the results with other citrus varieties and identify the field combination of vibration amplitude and frequency that reduces fruit damages using the experimental device.

References

1. Gupta, S.K.; Ehsani, R.; Kim, N.H. Optimization of a Citrus Canopy Shaker Harvesting System: Mechanistic Tree Damage and Fruit Detachment Models. *Trans. ASABE* **2016**, *59*, 761–776.
2. Whitney, J. Performance of mechanical citrus harvesters in Florida Optimization of a Citrus Canopy Shaker Harvesting System: Mechanistic Tree Damage and Fruit Detachment Models. In Proceedings of the International Society of Citriculture, Orlando, FL, USA, 3–7 December 2000; pp. 277–279.
3. Whitney, J.D.; Churchill, D.B.; Hedden, S.L.; Smerage, G.H. Trunk Shakers for Citrus Harvesting—Part I: Measured Trunk Shaker and Tree Trunk Motion. *Appl. Eng. Agric.* **1988**, *4*, 93–101. [CrossRef]
4. Savary, S.K.J.U.; Ehsani, R.; Schueller, J.K.; Rajaraman, B.P. Simulation study of citrus tree canopy motion during harvesting using a canopy shaker. *Trans. ASABE* **2010**, *53*, 1373–1381. [CrossRef]
5. Savary, S.K.J.U.; Ehsani, R.; Salyani, M.; Hebel, M.A.; Bora, G.C. Study of force distribution in the citrus tree canopy during harvest using a continuous canopy shaker. *Comput. Electron. Agric.* **2011**, *76*, 51–58. [CrossRef]
6. Liu, T.H.; Ehsani, R.; Toudeshki, A.; Zou, X.J.; Wang, H.J. Experimental Study of Vibrational Acceleration Spread and Comparison Using Three Citrus Canopy Shaker Shaking Tines. *Shock Vib.* **2017**, *2017*, 9827926. [CrossRef]
7. Ortiz, C.; Torregrosa, A. Determining adequate vibration frequency, amplitude, and time for mechanical harvesting of fresh mandarins. *Trans. ASABE* **2013**, *56*, 15–22. [CrossRef]
8. Castro-Garcia, S.; Aragon-Rodriguez, F.; Sola-Guirado, R.R.; Serrano, A.J.; Soria-Olivas, E.; Gil-Ribes, J.A. Vibration Monitoring of the Mechanical Harvesting of Citrus to Improve Fruit Detachment Efficiency. *Sensors* **2019**, *19*, 1760. [CrossRef]
9. Hedden, S.L.; Churchill, D.B.; Whitney, J.D. Trunk Shakers for Citrus Harvesting—Part II: Tree Growth, Fruit Yield and Removal. *Appl. Eng. Agric.* **1988**, *4*, 102–106. [CrossRef]
10. Brown, G.K. Mechanical harvesting systems for the Florida citrus juice industry. In Proceedings of the ASAE Annual Meeting, Chicago, IL, USA, 28–31 July 2002; Volume 021108; Appl Paper Number 021108.
11. Whitney, J.D.; Hyman, B.R.; Roka, F.M. The past, present and future of citrus mechanical harvesting. In Proceedings of the I International Symposium on Mechanical Harvesting and Handling Systems of Fruits and Nuts, Lake Alfred, FL, USA, 1–4 April 2012; Volume 965; Appl ISHS Acta Horticulturae 965.
12. Torregrosa, A.; Ortiz, C.; Martín, B.; Moreno, R.; Moltó, E.; Chueca, P. Mechanical harvesting of citrus fruits for fresh market with a trunk shaker and a hand-held petrol shaker. In Proceedings of the I International Symposium on Mechanical Harvesting and Handling Systems of Fruits and Nuts, Lake Alfred, FL, USA, 1–4 April 2012; Volume 965; Appl ISHS Acta Horticulturae 965.
13. Torregrosa, A.; Ortí, E.; Martin, B.; Gil, J.; Ortiz, C. Mechanical harvesting of oranges and mandarins in Spain. *Biosyst. Eng.* **2009**, *104*, 18–24. [CrossRef]
14. Moreno, R.; Torregrosa, A.; Moltó, E.; Chueca, P. Detachment and defoliation of citrus grown under Mediterranean conditions. *Span. J. Agric. Res.* **2015**, *13*, e02-006. [CrossRef]
15. Castillo-Ruiz, F.J.; Tombesi, S.; Farinelli, D. Tracking olive fruit movement and twisting during the harvesting process using video analysis. In Proceedings of the VIII International Olive Symposium, Split, Croatia, 10–14 October 2016; Volume 1199; Appl ISHS Acta Horticulturae 1199.
16. Federenko, Y. Movement modes of a fruit during vibration harvesting. In Proceedings of the International Conference on Sustainable Development of Cross-Border Regions, Barnaul, Russia, 19–20 April 2019; Volume 395, p. 012061; Conference Series: Earth and Environmental Science.
17. Spann T.M.; Danyluk, M.D. Mechanical Harvesting Increases Leaf and Stem Debris in Loads of Mechanically Harvested Citrus Fruit. *HortScience* **2010**, *45*, 1287–1300. [CrossRef]
18. Torregrosa, A.; Albert, F.; Aleixos, N.; Ortiz, C.; Blasco, J. Analysis of the detachment of citrus fruits by vibration using artificial vision. *Biosyst. Eng.* **2014**, *119*, 1–12. [CrossRef]
19. Ortiz, C.; Blasco, J.; Balasch, S.; Torregrosa, A. Shock absorbing surfaces for collecting fruit during the mechanical harvesting of citrus. *Biosyst. Eng.* **2011**, *110*, 2–9. [CrossRef]
20. Torregrosa, A.; Molina, J.M.; Pérez, M.; Ortí, E.; Xamani, P.; Ortiz, C. Mechanical Harvesting of Ornamental Citrus Trees in Valencia, Spain. *Agronomy* **2019**, *9*, 827. [CrossRef]
21. Ortiz, C.; Torregrosa, A. Damages Produced to Citrus Fruits During Detachment Using a High Amplitude and Low Frequency Shaker. In Proceedings of the EurAgEng Conference, Évora, Portugal, 4–8 July 2021.
22. Ortiz, C.; Torregrosa, A.; Castro-García, S. Comparison of a Lightweight Experimental Shaker and an Orchard Tractor Mounted Trunk Shaker for Fresh Market Citrus Harvesting. *Agriculture* **2021**, *11*, 1092. [CrossRef]
23. Hussein, Z.; Fawole, O.A.; Opara, U.L. Harvest and Postharvest Factors Affecting Bruise Damage of Fresh Fruits. *Hortic. Plant J.* **2020**, *6*, 1–13. [CrossRef]
24. Castro-García, S.; Rosa, U.A.; Gliever, C.J.; Smith, D.; Burns, J.K.; Ferguson, L.; Glozer, K. Video Evaluation of Table Olive Damage during Harvest with a Canopy Shaker. *HortTech* **2009**, *19*, 260–266. [CrossRef]
25. Jiménez-Jiménez, F.; Castro-García, S.; Blanco-Roldán, G.L.; González-Sánchez, E.J.; Gil-Ribes, J.A. Isolation of Table Olive Damage Causes and Bruise Time Evolution during Fruit Detachment with Trunk Shaker. *Span. J. Agric. Res.* **2013**, *11*, 65–71. [CrossRef]
26. Aragón-Rodriguez, F.; Castro-García, S.; Solá-Guirado, R.R.; Gil-Ribes, J.A. Fruit Abscission Pattern of 'Valencia' Orange with Canopy Shaker System. *Sci. Hortic.* **2019**, *246*, 916–920. [CrossRef]

27. Pu, Y.; Toudeshki, A.; Ehsani, R.; Yang, F. Design and evaluation of a two-section canopy shaker with variable frequency for mechanical harvesting of citrus. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 77–87. [CrossRef]

28. He, L.; Liu, X.; Du, X.; Wu, C. In-situ identification of shaking frequency for adaptive vibratory fruit harvesting. *Comput. Electron. Agric.* **2020**, *118*, 186–193. [CrossRef]

29. Sola-Guirado, R.; Castro-García, S.; Blanco-Roldán, G.L.; Jiménez-Jiménez, F.; Castillo-Ruiz, F.J.; Gil-Ribes, J.A. Traditional Olive Tree Response to Oil Olive Harvesting Technologies. *Biosyst. Eng.* **2014**, *118*, 186–193. [CrossRef]