Vibration analysis of the fruit detachment process in late-season 'Valencia' orange with canopy shaker technology

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Abstract

The mechanical harvesting of juice oranges can be achieved by the application of forced vibration to the tree canopy to detach fruit. Among the available harvesting technologies, canopy shaker systems have the advantage of working continuously, with rods that penetrate the tree canopy generating low-frequency, high-amplitude movement. The objective of this work is to analyse the fruit detachment process in order to improve the design and management of canopy shaker systems, reducing the risk of damage to fruit during the mechanical harvesting process. Three different canopy shaker systems were used to remove oranges in a well-adapted intensive orchard during the harvesting period. The fruit detachment process was recorded with a triaxial accelerometer sensor with a datalogger inserted into each tested fruit. Fruit movement displayed a similar frequency value as harvester rods (4.1-4.9 Hz), while the resultant acceleration depended on the interaction of the tree-machine system (38.8-60.4 m s^{-2}). The fruit detachment event occurrence required a vibration time ranging between 1.45-5.75 s, which can limit the machine's maximum speed. After the detachment event, fruit presented a short mean time (0.28 s) with no interaction with other fruit, branch or machine. The interaction of fruit during the harvesting process was more important, in terms of maximum acceleration, after the detachment event (527.6 m s^{-2}) than before (401.0 m s^{-2}). The use of a catch frame to collect fruit and of padding material in the machinery are fundamental measures to reduce the damage caused to fruit with canopy shaker technologies.

Keywords: *Citrus sinensis* (L.) Osbeck, mechanical harvesting, acceleration, vibration time, frequency

1. Introduction

Citrus production in Spain represents over 50% of the cultivated area devoted to this crop in the EU and more than half of its production, making Spain the sixth largest citrus producer in the world (FAOSTAT, 2014). Most of Spain's citrus production is destined for the fresh market, mainly within the EU, with about 5.4 million tonnes, followed by industrial processing, with approximately 1.4 million tonnes (MAGRAMA 2015). Citrus production is characterised by high volatility in both the price paid to the farmer and the availability of labour for hand harvesting. However, the juice market increases in importance in years when the price of the product decreases, which compromises the profitability of farms due to the high production costs involved.

The hand harvesting cost of fresh oranges in the south of Spain ranges between 0.045-0.05 € kg^{-1} (Junta de Andalucía, 2014), with values even higher than those of Florida for productive plantations destined for juice (Brown, 2005). The mechanical harvesting of citrus for juice could reduce harvesting costs by 50% and increase labour productivity by 10 (Roka & Hyman, 2012). In addition to sharing the significant obstacles that have been described for the adoption of mechanised citrus harvesting for industry in Florida, Spanish citrus orchards are aimed primarily at the fresh market and are hand harvested. Moreover, Spanish orchards are small, with non-adapted trees, which complicates the incorporation of harvesting technologies. The implementation of mechanical harvesting for citrus requires trunks aligned in a row, ample row distance and hedged trees with uniform tree canopies (Roka, Ehsani, Futch, & Hyman, 2014).

Canopy shaker systems are a harvesting technology that has been successfully employed for juice fruits for last three decades. These machines provide a continuous vibration of the tree canopy that allows fruit removal with greater precision than other shaker concepts (Whitney & Sumner, 1977). Canopy shakers can be regulated throughout the harvesting season to adapt the machine operating parameters to fruit characteristics (Sola-Guirado et al., 2016), but their success largely depends on the operator's experience (Savary, Ehsani, Schueller, & Rajaraman, 2010). Adaptation of canopy shaker systems allows the introduction of this technology to traditionally hand-harvested crops such as table olives (Ferguson & Castro Garcia, 2014) or oil olives (Sola-Guirado et al., 2014). Use of the same machine for several crops which have different harvesting periods would facilitate the market uptake of this type of system.

An adjustable and efficient harvesting technology could be of particular interest, especially for fresh fruit orchards, in years when market prices are low. In a first step, hand harvesting could be used for higher quality fresh fruit that is easier to pick. The second step would be the mass harvesting of remaining fruit that is more complicated and expensive to collect. A multi-use orchard, with both fresh and juice fruit, could improve a farm’s profitability, reduce economic uncertainty and minimise fresh market logistics (transport, handling and potential assignment for juice transformation) thus allowing farmers dual-purpose orchards depending on the period of the year.

Several different approaches have been adopted to study the detachment process of oranges with canopy shaker technology. The knowledge base was established by experimental determination of the strength properties of the twig-to-orange connecting joint in several loading modes (Alper & Foux, 1976). Interaction between the machine and canopy was analysed to improve harvesting efficiency and reduce tree damage, based on field measurements and simulation in branches (Savary et al., 2010; Gupta, Ehsani, & Kim, 2016). Torregrosa, Albert, Aleixos, Ortiz, & Blasco (2014) carried out direct measurement of the fruit detachment process with artificial vision in vibration laboratory tests. However, no studies have been performed on the fruit during the field mechanical harvesting process.

The objective of this study was to analyse the detachment process for sweet oranges using canopy shaker systems under field conditions. Vibration analysis of the time and frequency domains of the fruit detachment process could contribute to improving the design and management of this machinery, in addition to improving fruit removal and limiting the damage to fruit trees during mechanical harvesting.

2. Material and methods

Mechanical harvesting tests were carried out in Cordoba (Spain) during the sweet orange (*Citrus sinensis* (L.) Osbeck cv. "Valencia") harvesting season (5th May to 2nd June, 2016) when flowering was ending and before the natural immature fruitlets fell in June (Table 1). Trees were shaped into wide hedges, planted over 0.4 m ridges and had wide row distances to allow machine manoeuvrability. Four testing plots were used over the harvesting period. Fruit retention force (FRF) was determined using a manual dynamometer (Mecmesin CFG + 200, Slinfold, UK) adapted to traction tests with a 200 N range and 0.2 N resolution, in 40 oranges located on both sides of the tree canopy.

Field harvesting tests were carried out with three canopy shaker systems based on different mechanical principles for shaking (Figure 1). Each shaker system is outlined in patents of Briesemeister, Schloesser, Woodruff, & Russell (2008) US patent 7407166, Youman, Scott, & Schultz, (1999) US patent 5904034, and Sola-Guirado, Gil-Ribes, Blanco-Roldán, Castro-Garcia, Moreno-Martinez, et al. (2016) ES patent 2560353, for SC-1, SC-2 and SC3 respectively. The machines were drawn, powered and driven by a tractor. The first machine (CS-1) was a tractor-drawn canopy shaker (Oxbo 3210, Byron, New York) habitually used on farms. The other two were pre-commercial prototypes, from CPP Mecaolivar (see acknowledgments), adapted to mechanical citrus harvesting by the University of Cordoba in collaboration with the companies MaqTec Inc. (CS-2) and Moresil S.L. (CS-3). Table 2 shows the most important characteristics of each machine. The operating parameters of the machines were regulated in previous field tests based on previous experiences and recommendations for citrus harvesting (Peterson, 1998), resulting in a ground speed range between 1 and 1.5 km h-1 and a vibration frequency close to 4.5 Hz.

The fruit tested was located on the outer zones of the canopy, between 1 and 2 m high, where good contact with the shaking rods was ensured. Fruit vibration measurement during the mechanical harvesting process was recorded with an acceleration sensor that had been inserted into the fruit. A triaxial MEMS accelerometer sensor (Gulf Coast Data Concepts LLC X200-4, Waveland, MS) with a measurement range of ±200 g, 16-bit resolution, a sensitivity of 0.06 m s^{-2} and a sampling frequency of 400 Hz was used. Fruit was drilled with a 20 mm diameter, 80 mm deep hole in the blossom-end peel zone, without altering the fruit - peduncle union. The sensor was secured to the fruit with adhesive tape to avoid separation. The sensor weighed 48 g and was protected with a 10 g rubber sheath, which increased the fruit's weight by less than 10% (Figure 2). The fruit tested was selected on both sides of the trees. In total, 73 oranges recorded valid data, which corresponded to 32, 23 and 18 pieces for the SC-1, SC-2 and SC-3 machines, respectively. Vibration analysis was performed using NVGate v8.0 software, using a Fast Fourier Transformation with 401 lines in a frequency range of 0- 156.2 Hz with a 0.3905 Hz resolution.

Fruit movement during the canopy shaking process was recorded using a 3-axis acceleration sensor with a resolution of 0.0025 s. The majority of tested fruit was removed from the canopy during the canopy shaking process and the fruit detachment event was identified. The beginning of the shaking period was considered to be when any measurement axis exceeded the value of 10 m s^{-2}. The fundamental vibration frequency was determined from acceleration data before fruit detachment. The resultant acceleration in fruit was calculated as the vector sum of the values along each measurement axis (Castro-Garcia, Blanco-Roldán, Ferguson, González-Sánchez, & Gil-Ribes, 2017). The root mean square (RMS) value of the resultant acceleration was determined at 1.5 s before the detachment event, or at an intermediate time period if the fruit was not removed ($Acc_{\text{RMS before}}$). Five peak values of resultant acceleration were identified and averaged before and after the detachment event. The average of the five peak values of resultant acceleration before the detachment event ($Acc_{\text{max before}}$) represented the iteration process of the fruit with the tree canopy or the machine. On the other hand, the average of the five peak values of resultant acceleration after the detachment event ($Acc_{\text{max after}}$) represented the interaction process of the detached fruit with the tree -branches or fruit-, with the machine -rods or catch frame- or with the ground.

Data were processed by analysis of variance (ANOVA) and significant mean differences were separated using the Tukey post-hoc test that was accepted if $p < 0.05$.

3. Results

Fruit retention force values were distributed normally in each harvesting plot. Figure 3 shows the percentile distribution of FRF data measured in each harvesting plot. Harvesting plots 1, 2 and 3 had mean FRF values ranging from 62 to 72 N, with non-significant differences between them. However, the 90th percentile value of FRF for harvesting plot 4 was 114 N, higher than the values of the rest of harvesting plots, which had values of 83, 94 and 92 N, respectively.

The tested fruit was accessible to harvester rods and a value of 89% of fruit removal efficiency was reached. The oranges remaining on the tree after the canopy shaking process were 3, 1 and 4 for machines CS-1, CS-2 and CS-3, respectively.

The acceleration sensor recorded fruit movement during the canopy shaking process with high precision along the three-measurement axis. Figure 4 shows an example of the acceleration signal in the time domain of a horizontal measurement axis of the fruit. Before the detachment event, fruit presented periodic oscillation with increasing acceleration values and a fixed frequency value depending on machine regulation. During this time period, $Acc_{\text{max before}}$ identified the impact of the tested fruit with rods, branches or other fruit. Then, the fruit detachment was identified as a sudden event, which interrupted the periodic and forced movement of the fruit, leaving it in an interaction-free movement when acceleration values drastically reduced. After the detachment event, fruit fell with a high initial velocity (estimated at 4 m s^{-1} under simplifications of vertical free fall movement) interacting with the machine shaking system and the tree canopy. Finally, the fruit fell on the ground or into the catch frame, generating events with high values of $Acc_{\text{max after}}$.

The harvesting plots showed no significant mean differences in the vibration analysis results for the tested fruit. Consequently, vibration analysis results were grouped by machine and are shown in Table 3.

The mean values of vibration time before detachment event ranged between 1.45 and 5.75 s. Within this range, SC-3 showed the highest mean value (5.75 s) compared with other machines. This machine displayed an intermediate value of vibration frequency but with a reduced mean value of $Acc_{\text{RMS before}}$. The mean time when fruit had no interaction with other elements after the detachment event was 0.28 s, with no significant differences between canopy shaking systems. Similarly, the mean time after the detachment event when fruit interacted with other elements before coming to a complete halt was 1.25 s.

The three tested canopy shaker systems presented significant differences with respect to the mean value of vibration frequency (Table 3). Also, the vibration frequency values of each machine showed reduced variability, with a variation coefficient value less than 10% between the fruit. Vibration frequency and $Acc_{\text{RMS before}}$ values did not show a significant linear relationship (Coef. Pearson = 0.096, sig = 0.457, n = 63) for the tested canopy shakers. That is, the high values of vibration frequency did not correspond with high levels of acceleration in the fruit. The mean value of $Acc_{RMS\ before}$ was higher for SC-2 than for other machines, with mean values in the range of 38.8 -60.4 m s^{-2}. Mean values of $Acc_{max\ before}$ and $Acc_{max\ after}$ presented high values but with non-significant differences between machines. However, the mean value of $Acc_{max\ after}$ was higher than $Acc_{max\ before}$ (Paired-samples T test, t = 3.681, sig = 0.000). This result showed that the resultant acceleration peak values caused by fruit interactions after the detachment event (527.6 m s^{-2}) were more important than acceleration peak values before the detachment event (401.0 m s^{-2}).

4. Discussion

A canopy shaker system can achieve a fruit removal efficiency of 90-95% when the appropriate vibration parameters are used, it is operated by an experienced person and an adequate contact between canopy and rods is provided (Roka et al., 2014). In accordance with this assumption, the field test results showed a mean fruit removal efficiency of 89%. However, the fruit removal efficiency values ranged from a value of 95% for harvesting plot 1, with a reduced mean value of FRF (61.9 N), to 83% on harvesting plot 4, with the highest value of FRF (87.2 N). For high FRF values (102 N), Whitney (1999) reported similar values of 80% fruit removal efficiency, but required that rods penetrate the canopy beyond the trunk line. Subsequently, Peterson (1998) obtained values from 89 to 91% of fruit removal efficiency with FRF values in the range of 120-138 N.

However, the use of an abscission agent is not a common practice when canopy contact technology is used (Sanders, 2005). In fact, one of the main objectives of the abscission agent's development process was to improve the fruit removal efficiency of trunk shakers, where the use of such an agent is advisable (Burns, Roka, Li, Pozo, & Buker, 2006; Koo, Salyani, & Whitney, 2000). For a canopy shaker machine, the FRF value mainly influences maximum ground speed and, therefore, machinery field capacity (Burns, Buker, & Roka, 2005). Machinery field capacity, fruit removal efficiency and fruit and tree damage are related, and one of the main decisions is to find the best combination of these three elements (Torregrosa, Ortí, Martín, Gil, & Ortiz, 2009).

In order to achieve a high value of fruit removal efficiency, mechanical harvesting methods must overcome the obstacle of highly variable citrus fruit properties. Distribution of citrus fruit in the canopy can vary according to tree spacing (Whitney & Wheaton, 1984), secondary and fruit-bearing branches present a complicated distribution in the tree (Gupta, Ehsani, & Kim, 2015), and fruit production even varies between seasons (Moreno, Torregrosa, Moltó, & Chueca, 2015). Acceleration results obtained from the analysis of vibration in fruit showed the complexity of the movement of the fruit in the tree canopy and the large number of parameters involved in the detachment process (Torregrosa et al., 2014). However, vibration frequency values showed only a little variation due to its exclusive dependence on machinery adjustments. Vibration frequency is becoming an operational parameter to adjust before harvesting, whereas acceleration transmission to fruit will depend on machine and tree interaction.

Results showed that citrus fruit required a vibration time below a frequency value to reach the detachment event. According to the different results of the canopy shaker machinery tested, a mean citrus fruit required between 7.0 and 26.5 cycles of movements to achieve detachment. In similar tests, but under laboratory-controlled conditions and with a shaking mechanism, Torregrosa et al., (2014) required between 4.4 to 15.6 cycles. Also, these authors showed that an increment of amplitude could reduce the number of cycles required to achieve detachment. However, the difference between results may be justified because fruit in the canopy displayed increased movement when the machine moved towards them, increasing the amplitude of acceleration until their detachment (Figure 3). On the other hand, there was fruit that was not removed from the canopy that registered a high number of cycles without detachment. It could be that these oranges were included in the 90th percentile of high FRF values. However, it is known that the mechanical detachment of citrus fruit is strongly influenced by axial stress and that repeated loading by material fatigue has little effect (Alper & Foux, 1976). In any case, citrus fruit should be exposed to a vibration time or number of cycles accompanied by the appropriate vibration parameters if detachment is to be effective (Lenker & Hedden, 1968; Ortiz & Torregrosa, 2013).

To ensure the application of an appropriate vibration time and to achieve high fruit removal efficiency, canopy shakers can reduce ground speed or use longer rods, which increase machine contact with the canopy. However, these partial solutions can generate greater problems, such as economic considerations or dynamic resistance of the rod materials. From another perspective, Mateev & Kostadinov (2004) developed a probabilistic model to explain the harvesting process of Morello by vibration. These authors estimated that the quantity of non-detached fruit decreased exponentially when vibration time increased. Although it was possible to increase fruit removal efficiency by increasing vibration time, it did not seem appropriate to reach a value of 100% because this limited the machine's field capacity and increased damage to the tree. Field results support the research of Ortiz & Torregrosa (2013) who indicated that with fruit detachment by vibration, fruit removal efficiency usually presents a ceiling effect when vibration time is prolonged.

Mechanical harvesting with canopy shakers produces fruit detachment in a short time and allows the machine to continuously operate at an elevated ground speed. Shamshiri, Ehsani, Maja, & Roka (2013) reported a usual ground speed of 1.8 km h^{-1} for canopy shakers. However, the vibration time required to detach fruit, ranging between 1.45-5.75 s limited both the machine ground speed and its fruit removal efficiency. In field tests with the SC-1 shaking system, Burns et al. (2005) showed that mechanical harvesting at a ground speed of 3.2 km h^{-1} reduced fruit removal efficiency compared with 2.4 and 1.6 km h^{-1}. Therefore, they recommended the application of an abscission agent to increase machine ground speed without compromising fruit removal efficiency.

Fruit interaction with the canopy during the vibration process, before and after detachment, is usually an important component of the fruit damage caused by mechanical harvesting (Jiménez-Jiménez, Castro-García, Blanco-Roldán, González-Sánchez, & Gil-Ribes, 2013). The results showed that citrus fruits presented a short time (0.28 s) after the detachment event without interaction with other fruit, branch or machine, combined with a high level of $Acc_{max\ after}$. This time and the acceleration received by the fruit has an important role in preserving fruit quality, where fruit interception by catch frames or elevated canvases could reduce the impact suffered (Ortiz, Blasco, Balasch, & Torregrosa, 2011). Therefore, a coordinated design between machine and tree is necessary to preserve the quality of the harvested fruit. The canopy shaker system should be in permanent contact with the tree canopy to maintain vibration transmission, and tree pruning should facilitate the use of catch frames and reduce the probability of fruit impact.

Vibration frequency is a regulation parameter of the machine that can be transmitted from the machine to the fruit. However, the value of $Acc_{RMS\ before}$, as a result of the vibration in the fruit, obtained widely varying results. In the case of the trunk shaker, acceleration in the canopy has a direct relationship with vibration frequency (Castro-Garcia, Castillo-Ruiz, Jimenez-Jimenez, Gil-Ribes, & Blanco-Roldan, 2015). However, for canopy shakers, vibration frequency was not correlated with acceleration produced in the fruit. A good vibration transmission from the machine to the fruit is required to reach a high value of acceleration (Castro-Garcia et al., 2015; Sola-Guirado et al., 2014). Vibration transmission from the machine to the fruit could be improved through compression of the canopy by the shaking system, and by increasing the density of rods to ensure that fruit receives sufficient levels of vibration to achieve detachment. Nevertheless, both parameters can be the origin of increased damage to the tree and to fruit.

5. Conclusion

Citrus fruit located in the machine-tree zone of interaction showed complex movement during mechanical harvesting with canopy shaker systems. Although the fruit acquired the vibration frequency value of the machine, the values of resultant acceleration in the fruit depended on the interaction between machine and tree. The increment of vibration transmission from machine to tree should increase fruit removal efficiency. The vibration time required to achieve fruit detachment is the main limitation to increasing machine ground speed. Fruit quality is mainly compromised by the importance of the impact received after detachment. The design and use of a catch frame and padding material on the rods and surface of the machine are fundamental to reduce the damage caused to the fruit by impact received.

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Figures

Figure 1. Tractor-drawn continuous canopy shaker systems used in citrus harvesting tests. Left: CS-1: Oxbo,3210; Centre: CS-2: Mediolive Prototype; Right: CS-3: Samolive Prototype.

Figure 2. Placement of the acceleration sensor inside an orange before mechanical harvesting.

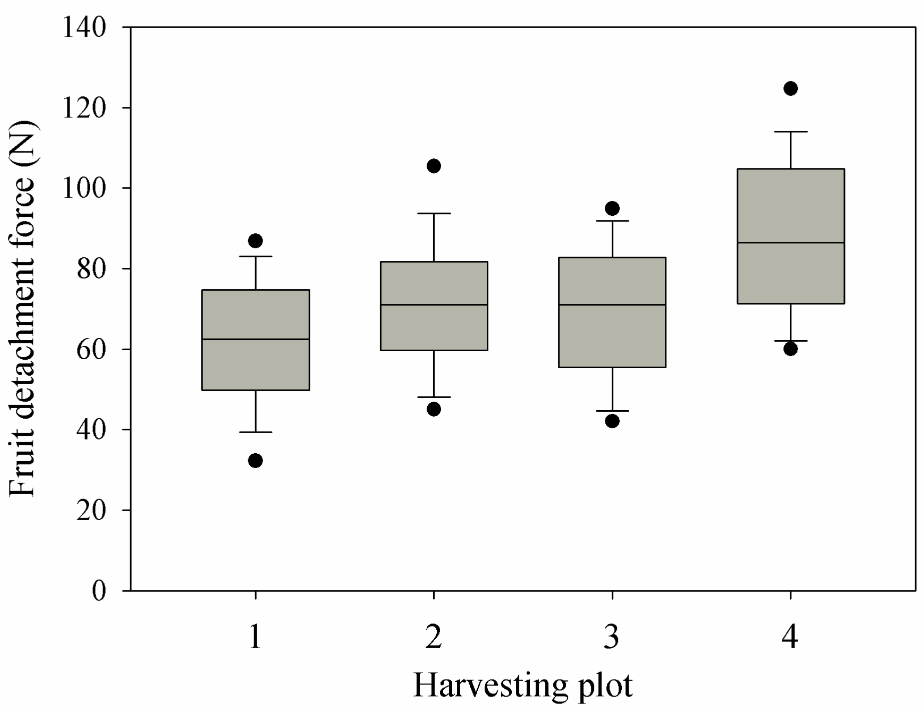

Figure 3. Percentile distribution of fruit detachment force in the harvesting testing plots.

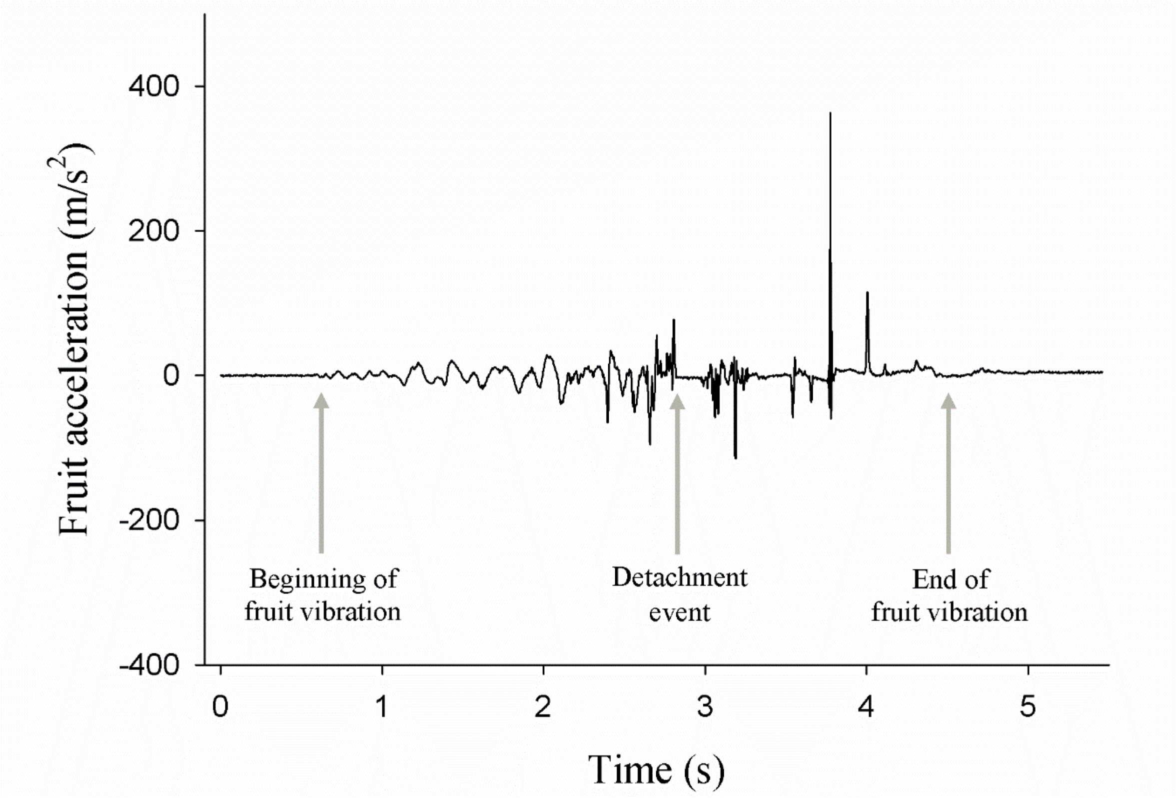

Figure 4. Example of a fruit acceleration signal in the time domain of a horizontal measurement axis during the harvesting process with SC-2 machine.

Table 1. Characteristics of citrus orchards mechanically harvested with canopy shaker systems.

	Plot 1	Plot 2	Plot 3	Plot 4
Distance between rows (m)	8	7	7	7
Tree distance in same row (m)	4	3	3	4
Hedge height (m)	3.9	4.5	3.5	4.5
Hedge width (m)	3.8	4.6	3.6	4.5
Trees per ha	288	440	440	330
Production (kg ha^{-1})	37,600	33,500	21,200	22,900
Fruit retention force (N)	61.9±15.2	71.5±17.3	70.2±16.7	87.2±20.8
Date planted	2005	2007	2007	2005

Values showed are mean ± standard deviation.

Table 2. Characteristics of tractor-drawn canopy shakers used in citrus harvesting tests.

	SC-1	SC-2	SC-3
Ground speed (km h^{-1})	1.5	1.0	1.0
Drums for rod holder	6	1	4
Total number of rods	288	156	120
Drums with canopy approximation	1	1	4
Vertical rod separation (m)	0.3	0.25	0.36
Rod length (m)	1.4	0.7	1.3
Catch frame	No	Yes	Yes

Table 3. Vibration analysis of tested fruit under mechanical harvesting with canopy shaker (SC) machinery.

	SC-1 (n=29)	SC-2 (n=22)	SC-3 (n=14)
Vibration time (s)			
Before detachment	2.39 (1.53) ^{a}	1.45 (0.87) ^{a}	5.75 (4.66) ^{b}
Interaction-free	0.34 (0.22) ^{a}	0.21 (0.10) ^{a}	0.26 (0.18) ^{a}
After detachment	1.16 (0.65) ^{a}	1.08 (0.56) ^{a}	1.71 (1.93) ^{a}
Total duration	3.98 (1.78) ^{a}	2.70 (0.94) ^{a}	7.76 (5.77) ^{b}
Vibration frequency (Hz)			
	4.1 (0.3) ^{a}	4.9 (0.3) ^{b}	4.6 (0.4) ^{c}
Acceleration (m s^{-2})			
$\text{Acc}_{\text{RMS before}}$	51.3 (31.2) ^{a}	60.4 (28.6) ^{b}	38.8 (13.7) ^{a}
$\text{Acc}_{\text{max before}}$	449.8 (226.3) ^{a}	409.6 (203.0) ^{a}	307.6 (150.1) ^{a}
$\text{Acc}_{\text{max after}}$	548.1 (197.2) ^{a}	549.8 (217.0) ^{a}	453.2 (237.8) ^{a}

Values shown are mean, with standard deviation in brackets ().
Same superscript letter in the same row is not significantly different (Tukey post-hoc test, $p \geq 0.05$).
$\text{Acc}_{\text{RMS before}}$ = resultant RMS acceleration value during 1.5 s before detachment event.
$\text{Acc}_{\text{max before}}$ = mean value of five impact acceleration before detachment event.
$\text{Acc}_{\text{max after}}$ = mean value of five picks of resultant acceleration after detachment event.