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Research Paper

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

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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 without stoppages between trees, 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 to improve the design and management of canopy shaker systems, reducing the risk of damage to tree and 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 and 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 contact with other fruit, branch or machine. The vibration of fruit during the harvesting process was greater, 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.

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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

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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.

Spanish orchards are small, with trees trained to manual harvest characterised by low skirts, globular canopy, reduced trunk height and ample number of main branches. Most of them are aimed primarily at the fresh market and are hand harvested. The picking cost of fresh oranges in the south of Spain ranges between 0.045 and 0.05 € kg^{-1} (Junta de Andalucia, 2014), with values higher than those of Florida, which ranged between 0.025 and 0.028 $ kg^{-1} (Singerman, 2015). Mechanical harvesting systems could reduce harvesting costs by 50% and increase labour productivity by 10 times (Roka & Hyman, 2012) but their feasibility depends on harvesting efficiency and damage suffered by trees and fruit. Previous experiences in Spain with trunk shakers for harvesting oranges and mandarins reported harvesting efficiency rates between 57 and 77% (Torregrosa, Ortí, Martín, Gil, & Ortiz, 2009). On the other hand, the continuous canopy shaker technology could increase the field capacity (ha h^{-1}) with a high value of harvesting efficiency (close to 90%), but requiring an ample row distance and hedged trees with uniform tree canopies (Roka, Ehsani, Futch, & Hyman, 2014). In both cases, fruit is destined for juice industry.

Canopy shaker systems are a harvesting technology that has been successfully developed for juice fruits for last three decades, mainly in Florida (Sanders, 2005). The canopy vibration is generated by the contact of the rods of the machine with the tree. These rods, also known as tines, have an alternating or rotational movement that penetrate and compress the tree canopy, producing impulse excitations on branches and fruits. The forced vibration of the tree canopy causes fruit detachment. The operating parameters of canopy shakers can be regulated throughout the harvesting season according to fruit characteristics (Sola-Guirado et al., 2016). The main machine operating parameters are the ground speed, vibration frequency, rod inclination and canopy compression by rods. Furthermore, 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 (Famiani et al., 2014; Sola-Guirado et al., 2014). Use of the same machine for several crops, which have different harvesting periods, would increase their utility and value, facilitating the adoption of this type of systems.

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 (Gupta, Ehsani, & Kim, 2016; Savary et al., 2010). Torregrosa, Albert, Aleixos, Ortiz, and Blasco (2014) carried out direct measurement of the fruit detachment process using image analysis in vibration laboratory tests. The fruit movement under field conditions, as response to a complex contact between the machine and canopy, is difficult to simulate or determine due to the ample number of fruit movement restrictions, the fruit interactions with canopy and machine and inaccessibility of the process. The direct vibration measurement on fruit during the harvesting process is a technique which could contribute to know information about the fruit movement during the harvesting.

The objective of this study was to analyse the detachment process for sweet oranges using canopy shaker systems under field conditions. The fruit vibration time and acceleration, before and after the detachment event, and vibration frequency were determined during the harvesting process with three different canopy shaker systems. Vibration analysis of the fruit detachment process could contribute to improving the design and management of this machinery, in addition to improving fruit removal and interception by catch frames.

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. The fruit retention force

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.

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