Frequency Response of Valencia Oranges to Selective Harvesting by Force Vibration

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Abstract

Citrus mechanical harvesting has been investigated since the 1960's. Even though mechanical harvesting could significantly lower production costs, the implementation by the private sector has been slow. The current harvesting technologies detach the fruits with trunk or branch vibration. For late-season sweet orange varieties which simultaneously bear mature fruit, immature fruitlets and flowers shaker harvesting decreases the following year's yield. This study investigated the frequency response of mature fruits and immature fruitlets to determine the optimum frequency range for an efficient and selective harvest. Laboratory vibration transmission tests were conducted with 14 branches bearing 76 mature fruits and 151 immature 'Valencia' fruitlets. A random noise vibration from 0 to 60 Hz was applied by a unidirectional electromagnetic shaker. The fruit and branch response to the forced vibration was measured by several sets of 5 triaxial accelerometers with a dynamic signal analyzer. Three frequency ranges with the highest vibration transmission values were identified for mechanical harvesting lower than 10 Hz. The first frequency range (1.5-2.5 Hz) corresponded best with the most efficient vibration transmission, involving more than 90% of fruit. The second frequency range (4.5-5 Hz) successfully discriminated between mature fruit and immature fruitlets. In this frequency range, 53.4% of mature fruit amplified the acceleration a mean value of 2.2 times, while only 7.3% of immature fruitlets amplified the acceleration with a mean value of 4.4 times. The lowest third frequency range had a vibration transmission value of 7-8 Hz. The frequency response of mature citrus fruits, and their markedly higher fruit mass, were significant factors in efficient selective mechanical harvesting.

1. Introduction

Mechanical harvesting of juice oranges has been a challenge since the 1960's. The development of mechanical harvesting methods has maintained an interest in reducing the production cost, while keeping the subsequent year's yield, preserving the tree health and producing quality fruit for citrus juice industry. Although current harvesting systems may increase labor productivity by 5 to 15 times whilst reducing the cost of harvesting up to 50% (Brown, 2005), its implementation is not widespread.

Indeed, mechanical harvesting methods have encountered a wide variety of obstacles to their adoption. The main obstacles comprise a possible yield reduction of the following season, mainly in late-season orange varieties (Roka et al., 2005); an increasing production costs for the fight against diseases such as Citrus Huanglongbing (HLB) and subsequent yield reduction; a need of providing an abscission agent to increase percentage of mature fruit removal; an unsuitability of trees and existing orchards to harvesting technologies; and a double aptitude of current plantations, as is the case of Spain, aimed either for the fresh or juice markets depending on the season's price (Moreno et al., 2015).

Mainly, citrus mass harvesters apply a given energy level to the tree in the form of forced vibration to detach the fruits (Sanders, 2005). Thus, the dynamic response of the tree and its organs depends on the parameters of the forced vibration. The excitation frequency of vibration can be generated in several ways to transmitted to tree. Harvesting technologies could be based on the rotation of an eccentric mass, a drum with sticks, a deflectors of a fan or a crankshaft-rod device. Usually, force vibration is applied to the tree with a constant stroke or amplitude, which in most cases is difficult to change without a machine or vibration frequency modification. As a result, the force vibration at the excitation frequency value is transmitted by the trunk, main branches, bearing branches to the fruit or other plant organs causing its detachment. In this complex process, the percentage of fruit removal also depends on several specific parameters of the fruit, such as its detachment force or mass, the position on the canopy and the duration or number of vibration events, among other factors. In fact, a number of previous works about field tests in citrus mechanical harvesting have shown promising results. However, the replication of these works is difficult due to the differences on machines, plantations, climatology, and plantation management, among others.

A special effort has been made in the late-season 'Valencia' orange variety, where simultaneously bear of mature fruit, immature fruitlets and flowers can decrease the subsequent year's yield when mechanical harvesting methods are applied. Development process of mechanical harvesting with trunk shakers showed that the use of a precise excitation frequencies together with an abscission agent, which reduced the fruit detachment force, were essential to obtain an efficient result without impacting the yield of the following crop (Burns et al., 2006). Thus, the use of an abscission agent is required to increase the percentage of mature fruit removal in late-season oranges with trunks shakers (Roka et al., 2005), but it seems unnecessary for canopy contact harvesters.

Current citrus mechanical harvesting methods show high values of percentage of mature fruit removal, but most of them only have crop selection ability (Sanders, 2005). In a step forward, the fruit size selection ability is required when late-season orange varieties are harvested to discriminate mature and immature fruits. This study aims to determine the frequency response of mature fruit and immature fruitlets under forced vibration in the range of excitation frequency of current harvest technology, in order to develop a selective mechanical harvesting process.

2. Materials and Methods

The vegetal material was obtained from a commercial citrus orchard (Citrus sinensis (L.) Osbeck cv. "Valencia late") destined for juice transformation located near the village of Hornachuelos (Cordoba, Spain). The plantation was 10 years old, featuring a good vegetative state and free of pests and diseases. The tree rows were trained in hedgerow with a height of 3.2 m, width 2.5 m and north-south orientation.

Laboratory test was carried out with 14 bearing branches with mature fruit, immature fruitlets but no flowers, which were cut during last week of July, 2015. Branches were selected according to both sides of canopy, along three rows of trees, including those representative branches bearing mature fruit and immature fruitlets. Branches were stored in cold storage at 5°C, HR 95%, with the cut-ending of the branch under water to prevent wilting, for up to 3 days to complete the tests. During storage period not wilting or loss of turgor was noticed on branches, fruits or leafs. The branches had mean values of 118 cm length, 3.1 kg weight, 251.8 L volume and 18.5 mm diameter at cut point.

For the laboratory tests, the branches were placed in a similar direction on tree canopy and fastened by means of a fixed end to measure their dynamic response under force vibration. The branch excitation was applied by a unidirectional magnetic shake (LDS, V406). The vibration generated was not sufficient to detach the oranges, fruitlets or other organs. The objective was to study the frequency response of the mature fruit and immature fruitlets. In order to avoid resonance phenomena in the branch or in the fastening system, the excitation signal used was a random noise with frequencies from 0 to 60 Hz, for a total duration of 60 s. The response of branch, mature fruit and immature fruitlets was measurement with a set of 5 piezoelectric triaxial accelerometers (PCB, 356A32). Several sets of measurements were recorded by branch according to the number of fruits.

In each branch, several sets of measurements were performed according to the number of mature and immature fruit. For each set of measurement, an accelerometer was placed at the point of application of vibration in the branch base. A total of 99 sets of measurement were performed. A dynamic signal analyzer with 16 measurement channels (OROS 36, Mobi-Pack) controlled by a vibration software (NVGate v.8) was used for generate the vibration signal, sensor conditioning, recording and analysis of the acceleration signals. A total of 888 acceleration signals were analyzed in frequency domain with 801 lines of spectral resolution in frequency range from 0.5 to 40 Hz with 0.5 Hz of frequency resolution. The root mean square (RMS) values of acceleration for each accelerometer axis ($\ddot{x}$, $\ddot{y}$ and $\ddot{z}$) was calculated for each vibration frequency (ω). The analysis of the vibrations was performed using the resultant acceleration value, that is, the vector sum of the three measurement axes on each accelerometer (Eq 1).

$$\text{Resultant acceleration} = A(\omega) = \sqrt{\ddot{x}^2(\omega) + \ddot{y}^2(\omega) + \ddot{z}^2(\omega)} \quad (1)$$

The acceleration transmissibility is a frequency dependent function, relates the effective acceleration of the mature fruit or immature fruitlet response ($A(\omega)_{fruit}$) with the effective input acceleration of the electromagnetic shaker applied to the branch base ($A(\omega)_{branch}$) according to Eq 2. For this ratio, values greater than one indicate vibration amplifications and values less than one indicate vibration reductions for each frequency studied.

$$\text{Resultant transmissibility } (\omega) = \frac{A(\omega)_{fruit}}{A(\omega)_{branch}} \quad (2)$$

3. Results

The 14 tested branches bore a total of 76 mature fruits and 151 immature fruitlets. However, one immature fruitlet and three mature fruits were discarded from the study for presenting damaged peduncles. The characteristics of mature fruit and immature fruitlets are shown in Table 1. At the test moment, the mature fruits showed 18 times more weight and volume than immature fruitlets, while the diameter of the stem holding the fruit to the tree was only 1.4 times higher in mature fruits.

Figure 1 shows the mean values of acceleration transmissibility from the base of the branch to mature fruits or immature fruits according to vibration frequency. The frequency response of fruit was different depending on the maturity stage. In both cases, acceleration transmissibility reached values higher than one (vibration amplification) for vibration frequency values lower than 10 Hz. Mature fruits showed the first two maximum values for acceleration transmissibility with 2.7 and 1.9 times at frequencies values of 2 and 4.5 Hz, respectively. Then, a minimum value of acceleration transmissibility (vibration reduction) at 6.4 Hz was identified. For higher frequencies values, an increase of acceleration transmissibility was observed with a maximum value (1.8) at vibration frequency value of 8 Hz. For frequency values higher than 10.5 Hz, acceleration transmissibility presented a vibration reduction from the branch to the mature fruit. Meanwhile, immature fruitlets showed two important values of acceleration transmissibility for frequency values of 2 and 8 Hz with a vibration amplification of 13.1 and 2.8 times, respectively. Immature fruitlets showed limited acceleration transmissibility values (<1) for vibration frequencies values above 18.5 Hz

Table 1. Properties of mature fruit and immature fruitlets in vibration tested branches (n=14).

	Mature fruit (n=76)	Immature fruitlets (n=151)
Distance between vibration and measurement (cm)	90.3±21.0 a	89.7±24.7 a
Stem diameter (mm)	3.9±0.7 b	2.8±0.4 a
Fruit weight (g)	253.7±49.1 b	14.1±3.8 a
Fruit diameter (cm)	8.2±0.6 b	3.1±0.3 a

Values showed are mean ± standard deviation. Same letter in the same row are not significantly different (T student, independent sample, $p < 0.05$) between mean values.

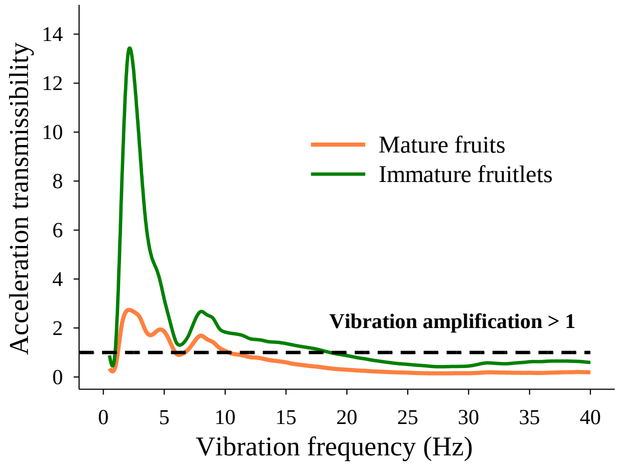

Figure 1. Mean values of acceleration transmissibility from branch base to mature fruit (n=74) and immature fruitlets (n=147) according to vibration frequency

Mature fruit and immature fruitlets showed a characteristic and proportional frequency responses represented by mean value of acceleration transmissibility (Figure 1). However, the individual response of each fruit varied from the mean value of the maturity set. Figure 2 provides a histogram of fruit percentage that contribute with a maximum value of acceleration transmissibility according to vibration frequency. Until five maximum values of acceleration transmissibility was considered in each fruit. The vibration frequency range was limited from 0.5 to 20 Hz, with 0.5 Hz of resolution, because the current mechanical harvesting methods operate into this range.

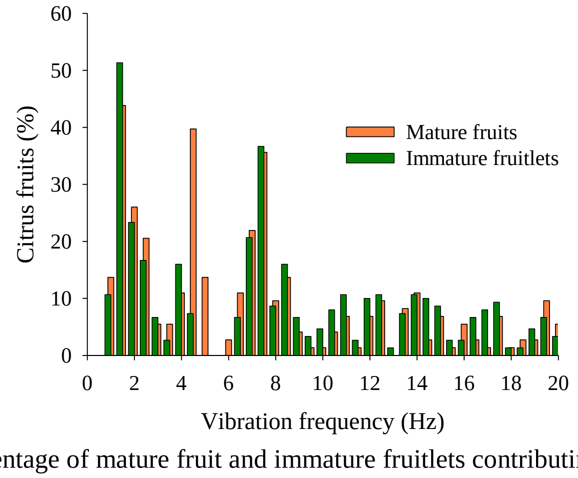

Figure 2. Histogram with percentage of mature fruit and immature fruitlets contributing with a maximum acceleration transmissibility values according to vibration frequency

Three frequency ranges were identified with a high percentage of fruit contributing with maximum values of acceleration transmissibility (Figure 2). Evidently, these ranges correspond with the maximum values of vibration transmission identified in Figure 1. The first frequency range corresponded with values from 1.5 to 2.5 Hz, and resulted in the most important response of fruit, both in acceleration transmissibility magnitude and percentage of fruit involved. In this frequency range, 91% of immature fruitlets amplified the vibration with a mean value of 16.2 times, while 90% of mature fruit amplified vibration received 3.4 times. The most important difference in frequency response of fruit according to mature stage was found in the frequency range from 4.5 to 5 Hz. At this second frequency range, 53.4% of mature fruit amplified the vibration a mean value of 2.2 while only 7.3% of immature fruitlets amplified the vibration 4.4 times. The third frequency range was set from 7 to 8 Hz. This frequency range involved similar percentage of mature fruit and immature fruitlets, 67.1% and 66% respectively. Besides, this frequency range showed high values of acceleration transmissibility for mature fruit (1.9) and immature fruitlets (2.9). Higher frequency ranges showed lower importance according to magnitude of acceleration transmissibility and percentage of fruit involved. However, some machinery can operate into these frequency values. For instance, frequency range from 11 to 14 Hz, reached acceleration transmissibility values of 1.1 and 1.7 for mature fruit and immature fruitlets, respectively. Also, this frequency range affected 43% of mature fruit and 53% of immature fruitlets.

4. Discussion

The results showed that there was a different frequency response between mature fruit compared and immature fruitlets in a narrow frequency range (4.5-5 Hz). This response might allow to develop a selective harvesting process of late-season oranges by forced vibration. However, at least two important limiting factors can affect the results in practical applications. Firstly, it is necessary to reach a high percentage of mature fruit removal (> 85%) with low impact on subsequent year's yield due to the inevitable detachment of immature fruitlets. At this point, the development and availability of efficient abscission agent has a decisive role for mechanical harvesting with trunk shakers. Secondly, the generation of a precise vibration frequency should be performed with suitable vibration amplitude able of produce a high acceleration values without damaging the trees. At this point, the properties of the machine to generate a forced vibration applied to trunk, branch or canopy contact are determining factors in the result.

Both mature fruit as immature fruitlets have shown higher acceleration transmissibility values in the frequency range 1.5-2.5 Hz. This response contributes to reach a high percentage values of fruit removal with mechanical harvesting methods which use a very low frequency values. Air blast shakers generate a force vibration with frequency values close to 1 Hz or 1.2 Hz and they can reach percentage of mature fruit removal of 90-95%. However, these machines also are efficient with immature fruitlets detachment, causing a yield reduction of the following crop with a mean value of 16% (Whitney and Wheaton, 1987). Also, air blast shakers require the use of abscission agent with a high input power requirement close to 242 kW contributing these machines have had a limited commercial development. The high frequency response of the fruit close to 2 Hz would correspond to the evolutionary response of tree to wind loads for a natural detachment of fruit. Wind loads are periodic and produces a complex movement of tree (James, 2003) that could contribute to the detachment process by natural causes of immature fruitlets and mature fruit (Sumner and Coppock, 1982).

The frequency range from 2.5 to 8 Hz involve an interesting responses of fruit, both in acceleration transmissibility magnitude and percentage of fruit involved as discrimination between mature stages (4.5-5 Hz). Into this frequency range is possible to operate with trunk or canopy tree contact technologies. Canopy shakers can operate in the frequency range from 2 to 6 Hz (Savary et al., 2010). However, in this frequency range the machine could be performed with large strokes values, usually ranged between 100 and 300 mm (Peterson, 1998; Castro-Garcia et al., 2009). So, high acceleration values are expected to be achieved on the tree canopy, with instant values up to 500 ms^{-2} (Savary et al., 2010; Sola-Guirado et al., 2014). These vibration parameters allow to achieve high percentage values of mature fruit removal (90-95%) if it has experienced operator, continuous and uniform canopies and trees less than 5.5m tall without the use of abscission agent. However, vibration applied directly to the bearing branches with high values of stroke might cause significant damage to the tree causing breakage of branches and stems (Spann and Danyluk, 2010). The ability of canopy shakers to get a high percentage of fruit removal is one reason of why these machines are spreading to other crops, such as olive orchards (Ferguson et al., 2009). Field test with early or mid-season oranges and canopy shakers have demonstrated that, under the correct vibration parameters selection, these machines does not affect neither the tree, nor the following yields (Roka et al., 2014b). However, its use with late-season oranges has reported subsequent year's yield reduction, mainly due to detachment of immature fruitlets, from 40% to 18% (Whitney, 1975). For late-season varieties is recommended to limit the use of these machines before the immature fruitlets had major changes in growth about six weeks after flowering or 22 mm in diameter, or more restrictive recommendations as 25.4 mm in diameter by early May (Roka et al., 2014a). Although canopy shakers can be operated into the frequency range with fruit size selective response (4.5-5 Hz), the vibration generated is highly energetic and efficiency in transmission in tree canopy. Then, the selective harvesting process with canopy shaker technology could be complicated to reach.

There are extensive studies about citrus mechanical harvesting with trunk shakers. These works show that, although the vibration frequency is an important parameter, its combination with a stroke value is essential for reaching a high percentage of mature fruit removal. However, in the frequency range up to 5 Hz, it is required that trunk shaker features a high stroke value which involve a heavy unbalanced mass to generate an enough acceleration level able to detach the fruit. Usually, a high stroke values is one of the most important damage source for machine and tree when inertial mass shakers are used (Abdel-Fattah et al., 2003). So, unidirectional vibration pattern for trunk shakers were developed to solve these problems with better results that multi-directional shaker. Anyway, the acceleration level issue has been addressed increasing the vibration frequency values, and losing the selective fruit ability, or with the application of abscission agent, which reduce the fruit acceleration levels required to detach fruit. In fact, Whitney et al. (2000) determined that if the abscission agent was not used, the percentage of mature fruit removal with trunk shakers would be 10-15% higher for low frequency and high stroke values (6-10 Hz and 50 mm) than for high frequency and medium stroke values (15-18 Hz and 30 mm). On the other hand, the requirement of acceleration level to detach fruit was reported by (Torregrosa et al., 2009) where the use of an inertial trunk shaker with reduced unbalance and eccentricity mass determined the vibration frequency values up to 9 Hz. Also, they reported that vibration frequency values in the range of 15-20 Hz produced a significant defoliation on the tree.

The reduction of fruit detachment force using an abscission agent facilitates the harvesting process by any method, and even increase the mechanical harvesting capacity (Burns et al., 2005). The percentage of mature fruit removal increased by 10-15% when the fruit detachment force of the orange is reduced 50-80% (Whitney et al., 2000). Abscission agent application was responsible to increase from 74 to 91% the percentage of mature fruit removal vibration in the trunk shakers (Hedden et al., 1988). Vibration frequency values close to 8-10 Hz combined with abscission agent application reported percentage of mature fruit removal from 90% to 95% (Burns et al., 2005).

The frequency range between 4.5-5 Hz has been identified as the opportunity to excite a large percentage of mature fruit (53.4%), with a low percentage of immature fruitlets (7.3%), keeping an important acceleration transmissibility value (2.2). However, it does not imply that this frequency range is the more effective for mature fruit detachment but it could be used for selective mechanized harvesting. (Burns et al., 2006) showed that trunk vibration at 4.8 Hz, without abscission agent, significantly removed less mature fruit than other treatments at 8 Hz. But, the application of abscission agent increased the percentage of mature fruit for both frequency values (89-97%). They reported that a 4 second vibration at 4.8 Hz significantly removed less immature fruitlets than 2 or 4 second vibration at 8 Hz. In fact, the abscission agent did not affect the detachment of immature fruitlets with trunk shaker. The differentiated frequency response of mature fruit could explain this result.

5. Conclusions

The analyses of the frequency responses of the mature fruit and immature fruitlets has identified three frequency ranges below 10 Hz with potential for mechanical harvesting of late-season 'Valencia' oranges. The first frequency range (1.5-2.5 Hz) correlated best with the most efficient vibration transmission, involving more than 90% of fruit. The second frequency range (4.5-5 Hz) successfully discriminated between mature fruit and immature fruitlets. The third frequency range (7-8 Hz) had the lowest vibration transmission value of all three frequency rages but involving close to 67% of fruit. The frequency responses of mature citrus fruits, and their markedly higher fruit mass, were the significant factors in efficient selective mechanical harvesting.

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