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Research Paper

Analysis of the detachment of citrus fruits by vibration using artificial vision

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The vibratory behaviour of citrus fruits is studied using slow-motion cameras in order to gain a better understanding of the parameters involved in fruit detachment when mechanical harvesting is done using shakers. Single citrus fruits with a small portion of stem were vibrated using strokes from 60 mm to 180 mm and frequencies from 3 Hz to 18 Hz. The movement was recorded at 300 fps and the main parameters considered for fruit detachment were determined through the analysis of the video sequences. Image-processing algorithms created for this purpose were applied to the automated estimation of the centroid of the fruit, the angle of the stem–pistil axis, and the position of some selected points in the fruit in each frame of the video sequences to obtain dynamic parameters such as the position, speed and acceleration of the fruit during the movement until it is detached. The signals obtained from the image processing were filtered, providing results in accordance with the calibration systems. In general, results suggest that the inertial forces transmitted to the fruit were lower than the tensile forces required to detach the fruit by pulling it in the stem–pistil direction. The largest peaks were observed using long strokes that required fewer cycles for detachment. On the other hand, short strokes combined with high frequencies needed more cycles, and thus a fatigue phenomenon was present. Short strokes and low frequencies were unable to detach some fruit.

1. Introduction

Citrus is a very important crop, with a worldwide production of 124 million tons in 2010 (FAO, 2012). Spain is one of the major producers with 5.9 million tons in 2010–2011 (Intercitrus, 2012), most of which were to be consumed as fresh fruit. But in recent years, prices have come to a standstill while production costs continue to rise. The implementation of advanced, competitive technology in agriculture allows a higher degree of modernisation of traditional agricultural tasks, thereby resulting in lower production costs and a more rational use of resources, which in turn fosters sustainability

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Nomenclature

a	linear acceleration (m s^{-2})
$\ddot{a}$	fruit angular acceleration (rad s^{-2})
α	angle between stem and fruit equatorial axis (degrees)
Abs(a_{max})	absolute maximum linear acceleration (m s^{-2})
Abs(v_{max})	absolute maximum linear speed (m s^{-1})
β	angle between horizontal and fruit equatorial axis (degrees)
CM	centre of mass
Δt	interval of time between two consecutive frames (1/300 s)
F	linear force (N)
Fd	traction force (N)
F_0	traction force at stem-polar fruit axis angle 0° (N)
Ft	tangential force (N)
f	frequency (Hz)
f_h	discrete function of Gaussian filter
fps	frame per second
Φ	phase displacement (rad)
h	interval between +wf and −wf
I	fruit moment of inertia (kg m^2)
IVIA	Instituto Valenciano de Investigaciones Agrarias
m	fruit mass (kg)
M	torque (Nm)
P_i	position of the centroid in frame i
P_{i-1}	position of the centroid in frame $i-1$
r	fruit radius (m)
RGB	Red Green Blue
SHM	simple harmonic motion
v	linear speed (m s^{-1})
V_i	speed measured for frame i
w	angular speed (rad s^{-1})
wf	window used for the Gaussian filter
X	half-stroke (m)
x	horizontal coordinate of a point
(xf_i, yf_i)	smoothed position points
y	vertical coordinate of a point

and competitiveness among growers. In this regard, harvesting is one of the most important factors affecting the price of citrus fruits in Spain because this task is currently done by hand. Mechanical harvesting is a promising alternative, especially the technique based on detaching the fruit by means of vibratory systems (Sanders, 2005). The mechanical bases of fruit detachment by vibration have been studied since the early 1960s, when the first branch and trunk shakers were constructed (Adrian & Fridley, 1958).

The frequency and amplitude of the shaking movements are some of the most important factors involved in the detachment of these fruits. In theory, natural frequencies cause the highest fruit displacements and therefore the highest detachment percentages are expected, but in practice Adrian and Fridley (1958) and Diener, Levin, and Whittengerger (1968) found that shaking at the natural frequency of most fruit was not very effective, with greater efficiency being achieved using higher frequencies. Similarly, Lenker and Hedden (1968) noted that citrus detachment increases with frequency.

Some theoretical models have been designed to study the phenomenon of fruit detachment. Parchomchuk and Cooke (1972) used a double pendulum to study the behaviour of the fruit–peduncle system, and compared the theoretical results with those obtained from the analysis of recorded images using slow-motion video sequences (160 fps). The model was highly predictive and they concluded that when there is a vertical component in the excitation, resonance happens at around twice the natural frequencies.

In crops such as apples or olives, the peduncle is a structure that is clearly different from the branch into which it is inserted and, hence, in the models defining the system fruit–peduncle, the area to be analysed can be clearly defined. But in the case of citrus fruits, the peduncle has a similar structure to the thin stem where it is inserted, but with a wide range of very different shapes and dimensions, thus making its analysis more difficult. For this reason, experimental trials are necessary to analyse the movement of this fruit.

In a similar line, Torregrosa, Ortí, Martín, Gil, and Ortiz (2009) studied the influence of frequency on detachment using an orbital trunk shaker that produced an amplitude of 2.5 cm. They tested frequencies of 9, 15 and 25 Hz in 'Orogrande' mandarins and in 'Salustiana' and 'Valencia' oranges, and found that detachment increased with frequency. However, as the frequency increased, so did the defoliation. Ortiz and Torregrosa (2013) shook citrus branches in the laboratory to analyse the effect of the frequency, amplitude and shaking time on detachment. They noticed that the point of detachment depended on the stage of maturity of the fruit, the variety and the traction force. High amplitudes and low frequencies achieved a higher percentage of fruit detached with the peduncle, but the effect was not significant so that these parameters could be used to control the detachment point.

Apart from frequency and amplitude, other factors are also important. Rumsey and Barnes (1970) studied several parameters related with detachment in 'Valencia' and 'Navel' oranges and 'Marsh' grapefruits. They measured the traction force necessary to detach the fruit as a function of the direction in which this force was applied, that is, following the calyx–pistil axis or following lines at 45° and 90° from the calyx–pistil line. They noted that the force decreased as the angle increased. In addition, they observed that a lower rate of detachment was achieved in fruits with longer peduncles, higher amplitudes being more effective. Moreover, they analysed the detachment point of the fruit in the traction tests and found that they were mostly detached without calyx whatever the traction angle. On the other hand, in torsion tests, most of the fruits were detached with calyx and the rest with peduncle, while in the vibratory tests the fruit detached with calyx decreased. Alper and Foux (1976) analysed the mechanical resistance of 'Shamouti' oranges to axial, flexion, torsion and combined forces. They separated the branches from the tree and performed the tests under laboratory conditions and found that axial strength was the main component to detach the fruit. When the force was applied with some inclination with respect to the calyx-bottom axis, the