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Simulation study on the effects of tine-shaking frequency and penetrating depth on fruit detachment for citrus canopy-shaker harvesting

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ABSTRACT

The overall low detachment percentage in citrus mechanical harvesting is a concerning problem. Studies of the effects of tine-shaking frequency and penetrating depth on fruit detachment for citrus canopy-shaker harvesting have not been reported to date. The objective of this study was to examine how tine-shaking frequency and penetrating depth affect fruit detachment based on simulation and pertinent field experiments for a citrus canopy shaker that inserts a row of shaking tines into the tree canopy. According to evaluation of the branch/stem elasticity, density, and fruit detachment force, a cantilevered limb model, including a periodic shaking force, was constructed to simulate the shaking process in citrus canopy shaking. Simulation results demonstrated a positive correlation between the shaking frequency and maximum stress at the fruit end of the stem, and a 5 Hz shaking frequency found to be sufficient for fruit removal. It was also observed that the penetrating depth ensured that, when shaking spot was close to the junction of the limb and stem, the maximum stress increased at the fruit end of the stem. Field trial results agreed with the simulation results, with both simulation and experiments indicating highly significant effects ($p < 0.01$) from both the tine-shaking frequency and penetrating depth on fruit removal. The simulation method used here can be utilized for improvements in canopy-shaker applications.

1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO) statistical report in 2009, citrus was ranked after banana as the world's second largest fruit crop with more than 122.3 million tons of production volume (FAO Statistics 2009). China is the largest producer of citrus with a cultivation area of more than 2 million hectares. In China, all citrus are harvested manually, but the labor costs are increasing quickly. Harvesting costs account for 35–45% of citrus production costs (Sanders, 2005). In America, citrus harvesting costs are also very high. For example, in 2012, the cost to hand-harvest sweet oranges for juice processing in the United States was more than \$1.90 a box (Muraro, 2012 and Roka et al., 2014). Mechanical harvesting is a viable solution for reducing harvesting costs.

Harvesting methods vary with the crop (Gupta et al., 2015). Mechanical harvesting has been successfully adopted for many crops, including some fruit and nut crops, such as blueberry, grape, almond, Chinese chestnut, pistachio nut, and dates (Peterson, 1998; Torregrosa et al., 2009, 2012; Arnó et al., 2012; Bao et al., 2014; Ding et al., 2016; and Wang et al., 2016). The importance and value of citrus have motivated intensive research into the development of mechanical citrus harvesting (O'Brien et al., 1983). The first research on mechanical citrus harvesting can be traced back to the 1950s. Research and development has resulted in trunk, limb, foliage, air, and canopy shakers for citrus harvesting. Adrian and Fridley (1965) has designed the first inertial-shaker, which applied a reciprocating force to primary limbs. Coppock and Tucker (1974) have stated that limb shakers have no observed effect on subsequent fruit yield in early and midseason orange trees. However, its harvest speed was slower than trunk and canopy shakers. Comparative trials performed by Hedden and Coppock (1971) have concluded that the foliage shaker performs better than any other harvester examined in their study. For harvesting citrus, Whitney (1968) and Whitney and Patterson (1972) have studied the air shaker, which does not contact the fruit and, thus, does not cause fruit bruising, but it is very noisy and its strong air stream can damage the tree. Peterson and Monroe (1974) have reported the development of a trunk-shaker mounted on a catching frame. In the late 1990s, a prototype similar to the current canopy shaker was designed and developed by Peterson (1998). Torregrosa et al. (2009) have found that the tractor shaker, with a detachment percentage rate of 72%, was functioning more effectively than handheld shakers, with an overall detachment percentage rate of 65%. Savary et al. (2011) have studied force distribution in the

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citrus tree canopy during harvest using a continuous canopy shaker. Torregrosa et al. (2012) have compared a trunk shaker and a handheld petrol shaker in the citrus harvesting process for fresh markets. Khorsandi et al. (2012) have applied a handheld limb shaker for harvesting Estahban's edible fig (Ficus Carica cv Sabz). Their statistical analysis showed that the shaking amplitude and frequency exert significant effects ($p < 0.01$) on detaching both ripe and unripe fruit. Zhou et al. (2013) have suggested a proper pruning of cherry trees to minimize the number and/or length of small and long twigs could contribute substantially to the improvement of the overall fruit removal efficiency by a shaking-based mechanical harvesting system. Ortiz and Torregrosa (2013) have studied the possibility of reducing frequencies and increasing amplitudes to achieve an optimal mechanical citrus harvest. Torreregrosa et al. (2014) have studied the vibratory behavior of citrus fruits using slow-motion cameras. Sola-Guirado et al. (2016) have developed and tested a canopy-shaker harvester on large olive trees and found that the vibration amplitude and frequency as well as the ground speed were the most important factors on the efficiency of fruit removal. Liu et al. (2017) have studied and compared how vibrational acceleration spreads along branches shaken by PVC, steel, and nylon tines for citrus canopy-shaker harvesting.

Computer simulation provides an efficient tool for determining the response of trees to practically any vibratory force (Gupta et al., 2015). Fridley and Lorenzen (1965) and Adrian and Fridley (1965) have simulated tree shaking by modeling the limb as a cantilever beam. Phillips et al. (1970) have programmed a computer algorithm to determine the vibrational characteristics of limbs with secondary branches. The Timoshenko beam theory has been applied to formulate differential equations for the dynamic responses of limbs (Schuler and Bruhn, 1973). Yung and Fridley (1975) have developed three special finite elements to mathematically describe a tree system. Upadhyaya et al. (1980) have studied the transient response of a limb under base impact, using Newmark's direct integration method. More recently, Savary et al. (2010) have developed a simulation framework for predicting interactions between the tree and canopy shaker using finite element methods. Gupta et al. (2015, 2016) have developed polynomial response surface models to predict sectional properties of the statistical model of tree limbs and proposed a progressive analytical approach for the design and optimization of a citrus canopy-shaker harvesting machine. Their optimized shaking method reduced by 40–45% the damage to limbs in the upper part of the tree canopy.

Because branches and stems in fruit trees are not in close contact with the shaking tine, as the shaker vibrates, shaking tines act on the tree canopy in a way that resembles an impact. That movement urges branches and stems to accelerate and decelerate, which spreads to the fruit, which then experience a detachment force, which, if bigger than the attached force, will remove the fruit from the tree. According to present studies, the key motion parameters of a shaking tine are amplitude and frequency. However, the tine penetrating depth might be important to fruit detachment as well. If the shaking parameters are correctly configured, fruit can be removed from the tree efficiently with low power consumption. The vibration amplitude depends on the structure of the shaking mechanism. For a certain citrus canopy-shaker machine, the shaking amplitude is difficult to change. However, the tine-shaking frequency and penetrating depth are very easy to adjust. Studies on the effects of tine-shaking frequency and penetrating depth on fruit detachment in citrus canopy-shaker harvesting have not been reported to date. The goal of this study was to develop a citrus canopy-shaker harvester that inserts a row of shaking tines into the tree canopy (Fig. 1a). The structure of shaking shaker and a schematic diagram of the shaker's workings are shown in Fig. 1b and c. In this study, a method for configuring both the tine-shaking frequency and penetrating depth for that shaker were studied by simulation and experiment. The specific objective was to achieve an understanding of how the tine-shaking frequency and penetrating depth effected fruit detachment for this citrus canopy shaker.

2. Simulation

2.1. Natural frequency analysis

When the limb is relatively thin and long and the fruit much heavier than the limb, it is assumed that the vibration of limb and fruit can be understood as a mass-concentrated vibration model. However, as most limbs are relatively thick, the quality of the limb itself must be taken into account. The mathematical model should include enough details to be able to describe the system in terms of equations, but without making it too complex (Rao, 2004). Before constructing the mathematical model, the limb was simplified as follows: (1) its centerline is a line; (2) its cross-section circular with one radius; (3) fruit attached at limb ends are centralized to a point; (4) the stiffness of its trunk and branch connection is much bigger than its own; and (5) the trunk and branch are static. A simplified mathematical model and force balance model for limb and fruit are shown in Fig. 2.

During shaking, there is no axial force applied along the limb and fruit. Because the limb has been simplified to a cylinder, according to vibration theory, the differential equation of motion for lateral vibration is

$$EI\frac{\partial^2 \mathrm{y}(x,t)}{\partial x^2} - \rho A\frac{\partial^2 y(x,t)}{\partial t^2} = -f(x,t) \tag{1}$$

where $\mathrm{y}(x,t)$ is the materials deflections, $f(x,t)$ the external force per unit applied on the limb length in the positive direction, which is upward, ρ the mass density of limb material, E the Young's modulus of the limb material, I the moment of inertia of the limb cross-section about the y-axis, and A the limb cross-sectional area. The boundary condition of the fixed end is $\mathrm{y}(x = 0,t) = 0$. The differential equation of fruit motion is expressed by

$$M\frac{\partial^2 \mathrm{y}(x,t)}{\partial t^2} = Q(l,t) \tag{2}$$

The boundary condition of fruit end is

$$EI\frac{\partial^2 y(l,t)}{\partial \mathrm{x}^2} = 0 \tag{3}$$

and

$$EI\frac{\partial \mathrm{y}(l,t)}{\partial \mathrm{x}} = -M\frac{\partial^2 y(l,t)}{\partial \mathrm{t}^2} = -M\omega^2 y(l,t) \tag{4}$$

The natural frequencies for the vibration system of the limb and fruit are computed using Eq. (5).

$$\frac{M\omega^2}{EI} = \beta^3\frac{1 + \cosh\beta l\cos\beta l}{\cosh\beta l\sin\beta l - \sinh\beta l\cos\beta l} \tag{5}$$

where $\beta = (\frac{\omega^2\rho A}{EI})^{1/4}$. The ratio of fruit and limb masses is $\alpha = \frac{M}{\rho Al}$. Therefore

$$\frac{M\omega^2}{EI} = \frac{\alpha\beta Al\omega^2}{EI} = \alpha l\beta^4 \tag{6}$$

Substituting Eq. (6) into Eq. (5) and rearranging it leads to

$$\alpha\beta l = \frac{1 + \cosh\beta l\cos\beta l}{\cosh\beta l\sin\beta l - \sinh\beta l\cos\beta l} \tag{7}$$

The roots of $1 + \cosh\beta_i l\cos\beta_i l = 0$, $\beta_i l$, give the natural frequencies of vibration, as expressed in Eq. (8).

$$\omega_i = \beta_i^2\sqrt{\frac{EI}{\rho A}} = (\beta_i l)^2\sqrt{\frac{EI}{\rho Al^4}} \quad i = 1,2,3,... \tag{8}$$

The roots, $\beta_i l$ ($i = 1,2,3,4$, and 5), of $1 + \cosh\beta_i l\cos\beta_i l = 0$ are listed in Table 1, which were obtained by a numerical analysis method using MATLAB 2016a (Mathworks, Inc., Natick, MA, USA).