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IFAC-PapersOnLine 49-16 (2016) 293–298

Effect of Fruit Location on Apple Detachment with Mechanical Shaking

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Abstract: Apples are picked manually every year around the world presenting challenges due to uncertain availability and the high cost of labor-force. To reduce dependence on seasonal labor and minimize harvest costs, shake-and-catch harvesting methods have been investigated in the past. However, these methods are ineffective in removing sufficient percentage of fruit from the trees, primarily due to the insufficient level of energy transferred to the desired branch locations. The primary goal of this study was to investigate the efficiency in detaching fruit from different locations of tree limbs. A fruit location index was formulated in this study to identify the location of targeted apples on a limb. A dynamic test system was developed to measure the dynamic response of fruit under certain shaking modes. From the experiment, fruit acceleration was found to be larger than 5 g when fruit location index was smaller than 2.5. It was also found the fruit ("Envy" variety) could generally be detached when the acceleration was higher than 5 g within the first 5 s shaking. Two harvesting tests (one on "Envy" variety, the other one on "Pink Lady" variety) were also conducted to verify the dynamic test results. The results showed that the majority of unremoved fruit were located where the fruit location index was greater than 2.5. This study indicated that the relative location of fruit in a limb with respect to the shaking location has critical influence on the fruit detachment efficiency. The study provided baseline information for improving the fruit canopy management and fruit removal techniques to potentially improve fruit removal percentage.

Keywords: fresh market apple, mechanical harvesting, shake and catch, fruit removal rate, fruit location

1. INTRODUCTION

Washington State is the largest apple producing state in the U.S., accounting for roughly 65 percent of national production in 2014 (USDA-NASS, 2015). Currently, highly labor intensive hand picking is the major method of harvesting apples for fresh market. Harvest labor costs account for more than 30% of production costs (Gallardo, 2011). This intense seasonal labor demand is creating a great risk of not having a sufficient supply of farm labor at critical times to conduct time-sensitive tasks. Harvesting, in particular, is threatened by the uncertain availability of labor. The apple industry needs technological innovations to assist growers in maintaining a competitive position in the global marketplace. Mechanical harvest is one of the key methods to address these challenges.

Vibration or shaking harvesting is one of the widely used methods for mechanical harvesting of tree fruit crops. The basic principle of harvesting with a shaking mechanism is to transmit kinetic energy to fruiting branches, which is used to generate a detaching force on the fruit-stem interface to remove fruit from the tree (Erdoğan et al., 2003). During shaking, a tree would respond differently to different excitation frequencies and amplitudes, and fruit removal occurs when the induced detachment force exceeds the pedicel-fruit tensile strength (Markwardt et al., 1964). Input vibration energy (shaking frequency and amplitude) and the physical characteristics of the tree/fruit system would be the major factors influencing the fruit removal efficiency. In a "Gala" variety, harvesting fruit removal efficiency averaged 35% across the fruiting section (limb) but averaged 88% within the actuation zone of the fruiting section, showing potential for a semi-selective harvesting technique to localize fruit removal on branches trained to trellis wires (DeKleine, 2014). Normally, the higher input vibration energy could result in higher fruit removal efficiency but with higher level of fruit and tree damage (Norton et al., 1962). Generally, a certain amount of fruit would remain on the tree after mechanical harvesting, which could be attributed to insufficient detaching force delivered to those locations due to unfavourable tree structure for mechanical harvesting (Diener et al., 1965).

In order to improve the fruit removal efficiency, investigation of the principle of fruit removal for different crops has been reported extensively since 1960s. Some studies focused on the physical properties and vibration characteristics of tree

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10.1016/j.ifacol.2016.10.054

limbs (Hussain et al., 1975; Castro-García et al., 2008; Gupta et al., 2015). Others focused on the stem-fruit dynamic response to different vibrations (Parchomchuk and Cooke, 1972; Crooke and Rank, 1969; Rand and Cooke, 1970). Fruit at different locations on a limb could also affect the fruit detachment effectiveness (Diener et al., 1965). In addition, point of attachment of of fruit in the different limb/fruit structures, e.g. directly attached, free limb, and hangers also affects effectiveness of fruit detachment techniques (Diener et al., 1965). Researches also suggested to shorten the long and small limbs (Fridley and Ching, 1975) and to adopt modern trellised systems (Zhou et al., 2016) to improve fruit removal efficiency in mechanical harvesting.

Most reported studies focused on using mathematical models to study the energy/force transmission in tree limbs or the detachment mechanism between fruit and stem. There are a few studies being reported on finding a quantitative expression of how the location of a fruit on a limb would affect fruit dynamic response and detaching force under certain vibrations. The primary goal of this study is to provide guidelines for mechanical harvesting of apples trained in modern fruiting wall orchard by investigating the vibration energy transmission to the apples at different locations. The specific objectives of this study are to: 1) Analyse the relationship between the fruit acceleration and fruit location in a tree canopy; 2) Validate the effect of fruit location on fruit detachment efficiency using a targeted (limb-level) shake-and-catch harvesting.

2. MATERIALS AND METHODS

2.1 Fruit Location Index

In this study, we primarily investigated the fruit location in trellis trained tree architectures (V-type or Vertical Fruiting Wall) (Figure 1 shows an example of V-type trellised trees). Trellised apple trees in Washington are often trained with six to eight horizontal levels of main limbs supported by trellis wires, with some twigs on each horizontal limb.

Fig. 1. Trellised apple trees of V-type fruiting wall canopy

Generally, apples either grow on both main limb and on twigs growing out of the main limb. Figure 2 illustrates a random limb with an apple located on a twig. In order to express the effect of fruit location on fruit detachment, a fruit location index was defined and used in this study.

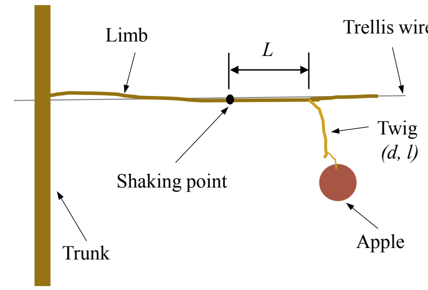

Fig. 2. An illustration of a typical trellis trained limb with fruit located at a twig

For each fruit, three indices, e.g. distance index, twig diameter index, and twig length index, were defined and used to represent its location effect with respect to the shaking point. The distance index (or $index_1$) represents the distance from the shaking point to the junction point of limb and twig bearing fruit, and defined as (1); twig diameter (or $index_2$) indicates the diameter of the twig bearing the fruit, and defined as (2); and twig length index (or $index_3$) represents the length of the twig bearing the fruit, and defined as (3).

$$index_1 = L_i / L_{mean} \quad (1)$$

$$index_2 = d_{mean} / d_i \quad (2)$$

$$index_3 = l_i / l_{mean} \quad (3)$$

Where, L_i, d_i, and l_i are respectively the distance from the twig-limb junction to the shaking point (middle of the limb), the diameter of the twig, and the length of the twig. L_{mean}, d_{mean}, and l_{mean} are the averages of corresponding variables over all the fruit tested in this study.
We defined fruit location index as the sum of these three major indices to identify fruit location in the limb (equation 4). Considering three dimensional (3D) location of the fruit, the relative angle of twig to the trellis plane/canopy plane could be another factor to define the location of the fruit, but was not performed in this study.

$$index_{fruit} = index_1 + index_2 + index_3 \quad (4)$$

2.2 Fruit Dynamic Response Test

To measure the dynamic response of apples with respect to certain input shaking frequencies, an experimental system was developed and a series of field tests was carried out to collect the baseline data need for this study (Figure 3). The experimental system consisted of an accelerometer (356A26, PCB Piezotronics, Inc., Depew, NY) that was mounted on the limb right next to the shaking point to measure the input excitation acceleration, and another accelerometer (356A16, PCB Piezotronics, Inc., Depew, NY) was mounted on the targeted apple. All tests were conducted on randomly selected V-type trellised "Envy" apple trees in a commercial Yakima Valley orchard in Washington in 2015 harvest season. The trellis system used in the orchard included seven metal trellis wires in both sides of a tree row to form a V-shaped canopy