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Research Paper

Effect of fruit location on apple detachment with mechanical shaking

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Fresh market apples are picked manually around the world. To reduce dependence on seasonal labour and minimise harvest costs, shake and catch harvesting methods have been investigated (no commercialised product). During shaking, certain amount of fruits could not be detached primarily due to insufficient level of transferred energy. The primary goal of this study was to investigate the efficiency in detaching fruit from different locations of tree branches in modern trellis-trained trees. A fruit location index was formulated and estimated to identify the location of targeted apples on a branch by considering the geometric dimensions of fruit bearing twig (twig index) and excited branch (branch index). A dynamic test system was developed to measure the response of fruit under certain shaking modes. The weights of twig index and branch index were optimised with maximizing R^2 of regression model between fruit acceleration and fruit location index. This study indicated that the fruit location has a critical influence on fruit detachment with shaking. Test fruits ('Envy' variety) could generally be detached within 5 s of shaking when fruit acceleration was higher than 5 g, and the corresponding fruit location indices were 0.071, 0.06, and 0.061 in three test frequencies. Harvesting tests showed that over 90% of fruits with location index greater than 0.06 were detached under 20 Hz shaking. Fruit quality assessment was not included in this study. The study provided baseline knowledge and information for improving the fruit canopy management practices to obtain high fruit removal efficiency.

1. Introduction

Apple is one of the most valuable fruit crops in the USA. The USA farmers grow around 5 million tons of apples on average with the wholesale value of approximately $4 billion and predicted additional downstream economic activities totaling roughly $14 billion each year (US Apple Association, 2016). Currently, hand picking is the only commercial harvesting method for fresh market apples, which is labour intensive and costly. What is more, the high demand for seasonal labour and the increasingly uncertain availability of labour pose a significant risk to growers, who may not have sufficient human

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resources for timely harvesting (Calvin & Martin, 2010; Fennimore & Doohan, 2008). The industry needs technological innovations for fresh market fruit harvesting, which will allow fresh market apple growers to remain competitive in the global marketplace. Mechanical harvesting is one of the key methods to address these challenges.

Mass harvesting with a vibration or shaking mechanism is one of the widely investigated 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 detach fruit from the tree (Erdoğan, Güner, Dursun, & Gezer, 2003). During shaking, trees respond differently to different excitation frequencies and amplitudes, and a fruit could be removed with one or combined motions of pendulum motion, tilting motion, twisting motion, and beam-column motion (Cooke & Rand, 1969; Diener, Mohsenin, & Jenks, 1965). Meanwhile, it was also found that stem fatigue during a repeated bending motion played an important role in fruit detachment removal (Rand & Cooke, 1970). Input vibration energy (shaking frequency and amplitude) and the biophysical characteristics of the tree/fruit system (including tree architecture, branch dimension, fruit variety, etc.) would be the major factors influencing the fruit removal efficiency. In our ongoing work, an average fruit removal efficiency (within the actuation zone) of 85% was achieved for 'Jazz' apples under shaking frequency of 20 Hz, showing a potential for a shake-and-catch harvesting technique to targeted branch/fruit section trained to trellis wires (Karkee et al., 2016). Input vibrations at higher frequencies result in better fruit removal efficiency, but they are often associated with a greater likelihood of damage to the fruit and tree (Norton et al., 1962). In contrast, lower frequencies may cause a proportion of fruit to remain on the tree due to insufficient detaching force delivered to fruit locations (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 branches (Castro-García, Blanco-Roldán, Gil-Ribes, & Agüera-Vega, 2008; Gupta, Ehsani, & Kim, 2015; Hussain, Rehkugler, & Gunkel, 1975). Others focused on the stem-fruit dynamic response to different vibrations (Parchomchuk & Cooke, 1972; Cooke & Rand, 1969; Rand & Cooke, 1970). Fruit at different locations on a branch could also affect the fruit detachment effectiveness (Diener et al., 1965). In addition, point of attachment of fruit in the different branch/fruit structures, e.g. directly attached, free branch, and hangers, also affects effectiveness of fruit detachment techniques (Diener et al., 1965). Researches also suggested to shorten the long and thin branches (Fridley & 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 branches or the detachment mechanism between fruit and stem. There are only a few studies reported on finding a quantitative expression of how the location of a fruit on a branch would affect fruit dynamic response and detaching force under certain vibrations. As fruit trees are increasingly trained towards more uniform and modernized architectures (SNAP: Simple, Narrow, Accessible, and Productive), the ability for mechanical harvesting to achieve high harvesting efficiency with good fruit quality is in reach (De Kleine & Karkee, 2015; He, Fu, Karkee, & Zhang, 2016). It is feasible to investigate the response of individual fruit within a targeted tree branch with modern architectures. 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 in energy transmission to the apples at different locations in a branch. The specific objectives of this study are to: 1) Analyse the relationship between the fruit acceleration and fruit location in a tree branch; 2) Validate the effect of fruit location on fruit detachment efficiency using a targeted (branch-level) shake-and-catch harvesting.

2. Materials and methods

2.1. *Fruit location index*

Because SNAP tree architectures are being increasingly adopted by tree fruit growers, all research tasks and experiments in this study were conducted in orchards with SNAP fruiting wall canopies in WA, USA (Fig. 1 shows an example of V-trellis fruiting wall architecture). Those trellised apple trees in Washington State are often trained with six to eight primary branches trained horizontally to trellis wires, with some twigs grown laterally from those horizontal branches (also called formal training system).

It is essential to understand the natural growth of branches and fruit in those tree canopies and their response to shaking input so that targeted shake-and-catch harvesting system can be optimised to achieve desired level of performance. For the formally trained trees with branches trained to trellis wire, one section of a horizontal branch and fruit in that section could be viewed as the basic unit of the overall tree canopy. Generally, apples either grow on both main branch and on twigs growing out of the main branches. Figure 2 illustrates a

Fig. 1 – Apple trees with V-trellis canopy architecture in WA, USA.