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Enhancing Mechanical Fruit Harvesting Machines Based on Vibration Analysis

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Enhancing Mechanical Fruit Harvesting Machines Based on Vibration Analysis

by

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In

Mechanical Engineering

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The dissertation of Taymaz Homayouni is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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University of California, Merced

2021

To my parents, my sister and my beautiful wife, Shirin.

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- Ruijun Ma, **Taymaz Homayouni**, Arash Toudeshki, Reza Ehsani, and Xiaohua Zhang. "An experimental study and mathematical modeling of vibration transfer in pistachio trees using an inertia-type trunk shaker and field-adapted wireless sensors. " *Shock and Vibration*, (Under Review).
- Afsah-Hejri, Leili, **Taymaz Homayouni**, Arash Toudeshki, Reza Ehsani, Louise Ferguson, and Sergio Castro-García. "Mechanical Harvesting of Selected Temperate and Tropical Fruit and Nut Trees." *Horticultural Reviews*, *Volume 49* (2021): 171.
- Gholami, Akram, **Taymaz Homayouni**, Reza Ehsani, and Jian-Qiao Sun. "Inverse Kinematic Control of a Delta Robot Using Neural Networks in Real-Time." Robotics 10, no. 4 (2021): 115.

- Afsah-Hejri, Leili, Arash Toudeshki, **Taymaz Homayouni**, Shirin Mehrazi, Akram Gholami Pareh, Phoebe Gordon, and Reza Ehsani. "Potential of ozonated-air (OA) application to reduce the weight and volume loss in fresh figs (Ficus carica L.)." Postharvest Biology and Technology 180 (2021): 111631.
- Afsah-Hejri, Leili, Elnaz Akbari, Arash Toudeshki, **Taymaz Homayouni**, Azar Alizadeh, and Reza Ehsani. "Terahertz spectroscopy and imaging: A review on agricultural applications." Computers and Electronics in Agriculture 177 (2020): 105628.

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List of Symbols

a_r	Resultant acceleration
a_x	Acceleration along x axis
a_y	Acceleration along y axis
a_z	Acceleration along z axis
E	Kinetic energy of a unit length
λ	Sensor location index
L_i	Distance of *i*th bifurcation point from the previous one in m
D_i	Diameter at *i*th point
ρ	Density
F	Force
m	a
a	Acceleration
V	Volume of unit length
v	Velocity
c_k	Coefficient of function
v	Velocity
λ	a
v	Velocity
λ	a

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Abstract

Currently, fruit removal using multi-directional canopy and trunk shakers are the most widely used technique for harvesting nut trees. To develop an intelligent harvesting machine, a system needs to be developed to shake each tree optimally. Optimum mechanical harvesting machines aim to maximize fruit removal with minimum tree and fruit damage, using the least amount of energy. Maximum fruit removal requires the tree to be shaken around its natural frequency; however, the best shaking frequency is not the same for all trees. The natural frequency of a tree is a function of its morphology, size, mass, branch configurations, wood properties, and density of leaves. The natural frequency could also change during harvest. For instance, when a tree is shaken and fruit drops, the natural frequency shifts due to changes in the mass.

In this work, vibration transmission in trees is studied to enhance mechanical harvesting machines while minimizing damage to the tree. Trunk shakers and canopy shakers are the most common commercial mass harvesting machines, each comes with a limitation. Further, a trunk shaker has more energy loss from tree trunk to its canopy compared to a canopy shaker.

The efficiency of the commercial harvesting machines is evaluated by quantifying the energy input to the trunk and the transferred kinetic energy throughout the tree canopy. A set of wireless accelerometer sensor systems was developed and used to measure acceleration at different parts of the tree and the shaker machines. A mathematical model of vibration and force transmission throughout a pistachio tree is developed under different shaking conditions using a trunk shaker. A new method was developed to find proper shaking intensity as a function of the tree trunk size. Two canopy shakers were designed, fabricated and tested in the field for harvesting table olive trees. One design included an adjustable head, and one included a large canopy shaker for larger mature trees. It was found that a combination of canopy and trunk shaker results in the highest harvesting efficiency in olive trees.

Chapter one is mainly a review of literature of different types of mechanical harvesting methods. Chapters two and three are focused on mathematical modeling of variation and force throughout a pistachio tree while shaking using a trunk shaker. Chapters four and six presents two new canopy shakers specifically designed for table olive harvesting. The effectiveness of using two shaker machines at the same time is discussed and evaluated in Chapter five.

Chapter 1

Introduction to Mechanical Harvesting

Handpicking, the traditional method of fresh fruit harvesting, includes two steps: picking and field collection. For field collection, the filled bins or boxes are transported to a central location where they are loaded onto trucks and transported to packinghouses or processing plants (Whitney, Hyman, & Roka, 2012). The efficiency of manual harvesting depends on the skill level, speed, and physical strength of workers, fruit density, fruit accessibility, and environmental conditions (Prussia & Woodroof, 1986). To lower variability and reduce the worker-performance dependency of manual harvesting, mobile platforms, picker positioners, and picking aids were designed to enhance the performance of workers (Coppock & Jutras, 1960).

Manual harvesting is expensive, time-consuming, and labor-intensive (Li, Lee, & Hsu, 2011) with harvesting costs constituting 45 to 50% of the total operational costs (Sanders, 2005)Mechanical harvesting can reduce the number of workers, increase harvest efficiency, and enhance net return. Depending on the type, size, and shape of the tree trunk and canopy, one of the following mechanical harvesting technologies can be used: 1) comb brushing, 2) shaking, or 3) impact harvesting. Most commercial harvesters use shaking. In this method, a contact head transmits the vibration energy of the machine to the tree and results in fruit detachment (Du, Chen, Ma, Wu, & Zhang, 2020). Air blast, trunk shaking, canopy shaking, and limb shaking are all common mechanical harvesting methods. A foliar pre-harvest abscission chemical spray is sometimes used to initiate abscission from the fruit petiole and catching frames are used to reduce fruit damage and collect the fruits (Li et al., 2011).

A fruit tree can be described as a vibrating system consisting of the vibrating tree canopy, trunk and limbs, and the root-soil mass (Horvath & Sitkei, 2005). Improper clamping and excessive vibration can result in high energy distribution to the vibrating tree, damage to the bark, and a reduction in productivity. To achieve an efficient harvest without tree damage, it is crucial to select the right harvesting method and to apply an appropriate force at the proper location. These factors vary according to the type, size, and architecture of the tree. Other factors such as weight, shape, size, and maturity level of the fruit are also important in selecting an appropriate harvesting method. This review examines the different mechanical harvesting methods for a number of selected temperate and tropical nut and fruit trees and discusses the factors affecting mechanical harvesting. It also discusses smart harvesting techniques, current challenges, and gives an overview of mechanical harvesting and its future.

Part of this chapter has been published in (Afsah-Hejri et al., 2021).

1.1 Mechanical Harvesting Methods

Studies on mechanical harvesters were initiated in the early 1960s, when the horticulture sector, including the fresh fruit industry, experienced an inadequate labor supply. Researchers focused on motion and time studies to improve conventional harvesting methods with the addition of mobile platforms or picking aids (Whitney et al., 2012). Later, during the 1970s, abscission chemicals were developed and used with mechanical harvesters or mass harvesters using air blast or trunk shakers (Li et al., 2011). Figure 4.1 shows some of the mechanical harvesters that are commonly in use.

1.1.1 Human Harvesting Aids

The major limitation in manual harvesting is the limited height a human can reach. Human positioners and mobile platforms were designed to replace ladders and to increase harvest efficiency (Coppock & Jutras, 1960). Mobile platforms increased productivity by 30 to 40%; however, the initial investment cost was high (Hedden, 1964). Under Pennsylvania (USA) conditions, apple orchards with yields of 25 to 45 Mg ha^{-1}, and areas greater than 7.6 ha can economically incorporate mobile platforms (Zhang & Heinemann, 2017). Zhang et al., (2016) demonstrated that a modified self-propelled mobile platform from the ORSI group (Bologna, Italy) and an improved fruit distributor, increased harvest efficiency of canopy top apples by 95%. The major source of efficiency was the elimination of the time to position a ladder. Harvesting platforms improve the efficiency, safety and ergonomics of workers (Fei & Vougioukas, 2021). However, most current harvesting platforms systems lack efficient, coordinated fruit collection systems and workers are still wearing individual buckets and bags (Zhang, Lu, & Igathinathane, 2020).

1.1.2 Mechanical Harvesters

Multiple mass harvester prototypes have been researched and fabricated, but very few have been commercialized. This is generally the last and major step in developing a successful mechanical harvesting system. The first steps in developing successful mechanical harvesting are developing a fruit removal method and demonstrating that it can produce a marketable fruit. The third step is simultaneously improving the harvester parameters and adapting orchards, primarily the canopies and trunks, to improve final harvest efficiency. Final harvest efficiency is defined as the fruit weight collected as a percentage of fruit weight on the tree; fruit dropping to the ground is not included. The fourth step is developing the harvesting parameters; the amplitude and force applied, ground speed of the mobile platform and collection logistics. All these steps usually are done within university research programs which produce prototypes and operating parameters. The final step, fabrication of a viable commercial harvester, is done commercially and is based on potential sales.

Currently, the most common mechanical harvesters are trunk shakers and canopy shakers. The shaking parameters for both are based on duration, amplitude, and frequency. The highest amplitude is observed at the shaking point and decreases with distance, the farther the branch the lower the amplitude.

1.1.2.1 Limb Shakers

Limb shakers were developed to improve the efficiency of manual harvesting. These devices significantly reduced the time required for fruit harvesting (R. Sumner & B. Churchill, 1978) and limb shakers helped workers to reach the highest parts of a tree canopy (Louise Ferguson, 2006). Phillips et al. (1970) performed one of the earliest studies on limb vibration response using finite element analysis to improve mechanized harvesting, considering the different distributions of fruit mass and secondary branches in the tree. Limb shakers mostly use a crank-slider or rotating-mass mechanism to generate vibration motion. Sumner et al. (1978) compared the effect of these two mechanisms on orange removal. They identified that the rotating-mass system produced a smoother shaking motion when compared with the crank-slider mechanism. Sessiz and Özcan, (2006) developed a pneumatic branch shaker and achieved an efficiency of 50% without the application of abscission chemicals.

One of the main concerns associated with limb shakers is the bark damage that can occur at the attachment point (Fridley, Brown, & Adrian, 1970). Severe damage by the shaker boom may damage the xylem and phloem under the bark and reduce yields. Although hand-held limb shakers improved manual harvesting efficiency, they cannot be considered truly mechanical harvesters: a) there is no collection mechanism, and b) the speed and efficiency of these units are determined by the operator (Louise Ferguson, 2006). Limb shakers have several problems. They expose the operator's hand to vibration and transmit vibration to the hand-arm system causing muscular/skeletal syndromes variously described as Hand-Arm Vibration Syndrome (HAVS), Carpal Tunnel Syndrome (CTS) and Vibration-Induced White Finger (VWF) (Catania, Bono, & Vallone, 2017).

1.1.2.2 Air Blasts

High-speed, turbulent airflow can detach fruits from a tree. Air blast machines were initially developed in 1961 using an oscillating air pattern (Jutras, Coppock, & Patterson, 1963). Whitney and Patterson (1972) subsequently developed an air blast system that generated airflows up to 100 mph (160 km h^{-1}). However, such machines are heavy due to the size of the engines and fans that are used to create the needed energy, 186 to 260 kW, and are therefore impractical (Whitney, 1977). Air blast harvesters were tried for apple harvesting but never became popular due to the high fruit damage that occurred (Berlage, 1973). Oscillating air blast harvesters have been tested with abscission chemicals for olive (Louise Ferguson, 2006) and citrus harvesting with limited success.

1.1.2.3 Trunk Shakers

Trunk shakers were first introduced in the early 1960s (Affeldt Jr, Brown, & Gerrish, 1989). Fridley et al. (1970) measured the maximum radial, longitudinal and tangential stresses that did not result in trunk or limb damage in apricot, peach, almond, plum, and olive trees. They found that the maximum radial stress was between 500 to 1000 psi (3.5 to 6.9 MPa) and that the maximum longitudinal and tangential stresses were about one-fourth and one-third of the radial stress, respectively. A high rate of fruit bruising is the main problem associated with trunk shakers (Li et al., 2011). A trunk shaker's efficiency is affected by the damping effect of the trunk and branches (F Jimenez-Jimenez et al., 2015; Sola-Guirado et al., 2014). High energy needs to be applied to the tree trunk to achieve acceptable harvest efficiencies.

During the 1970s and 1980s, multiple modifications of trunk shakers improved their performance and reduced tree damage. These modifications included: a) adding an adjustable eccentric using pitman arms (Harrett, 1963); b) adding a variable offset mass to create the desired shaking patterns (Fridley, 1970); c) changing the eccentric force of the shaker through changing its rotational velocity (Gould & Richter, 1971); d) creating various geometric paths by using a "walking" sun-gear shaft (Hood Jr, Alper, & Webb, 1979); and e) adding a controllable, variable-eccentric mass to eliminate excessive vibration and reduce bark damage (Affeldt Jr et al., 1989). Trunk shakers are now commonly used in nut crops (pistachio and almonds) and processing fruits (prunes and cherries).

1.1.2.4 Canopy Shakers

An alternative to trunk and limb shakers is the canopy shaker, also known as a canopy contact shaker. The machine uses a series of rods attached to an eccentric wheel that shakes the tree canopy. The rods can also come into contact with tree branches and periodically impact tree limbs and shake the whole tree canopy, causing fruit removal. There are two types of canopy shakers: (1) continuous canopy shaker with a catching frame for collecting harvested fruits; (2) tractor-drawn canopy shaker which drops the fruits to the ground. Like other methods, shaking amplitude and frequency were determined to be the most important parameters determining canopy shaker efficiency. High amplitudes may break or damage branches, while too little amplitude may be too low to detach fruits. Maintaining contact between the canopy shaker and tree canopy is essential for efficient harvesting. Recently, Pu et al. (2018) developed a canopy shaker with a new shaking mechanism that could move in and out of the mainframe to maintain continuous contact with the tree canopy.

1.1.2.5 Catching Frames

Fruit harvesting consists of two components: fruit detachment and fruit collection. The early trunk and limb shaking harvester prototypes did not have fruit collection methods. Workers collected fruit from the ground, increasing the risk of contamination. In 2002, Vieri developed a trunk shaker with a catch frame in the shape of an upside-down umbrella (Vieri, 2002). Zion et al. (2011) developed lightweight under-tree nets rolled out under the tree to collect the detached fruits from trunk and limb shakers on the opposite side of the tree. Since 1970, two-sided trunk shakers with two separate machines moving simultaneously on both sides of a tree have been used in nut crops and prunes. The trunk shaker head is attached to one machine, and the other side has a conveyer belt mechanism to collect the fruits. On each of these machines, large, flat-slanted surfaces, wings, facing the tree canopy collect and guide fruit to the lower parallel conveyer belt system (Ravetti & Ravetti, 2008) which transfers the fruit into field bins or bank out wagons. The bins are left in the field for later collection. The wagons have larger fruit storage and have a central screw for distributing the crop within the wagon. These wagons have cabs at both ends that can detach from the harvester when the wagon is full and be replaced with a new wagon (Menezes, Mateus, & Ravetti, 2019).

1.2 Smart Harvesting

The adoption of the Global Navigation Satellite System (GNSS), imagery from satellites and unmanned aerial vehicles (UAV), and the use of artificial intelligence (AI), deep learning (DL), and machine learning (ML) within agriculture has led to more efficient, higher-yielding production systems. The adoption of new technologies in harvesting machines is an integral part of these developments.

1.3 Knowledge Gap and Objectives

Current mechanical harvesting machines rely heavily on experienced operators to establish the shaking parameters, including shaking frequency and duration. Variation in tree size, shape, and yield change the optimal harvesting parameters that are required for the most efficient harvest of each tree. The next generation of harvesting machines should be less dependent on operator judgment and more able to independently set the optimal shaking parameters for each tree.

Current shakers can create different shaking patterns by changing shaking intensity vs. time. These patterns can be programmed into the shaker's computer control system. This allows the operator to adjust the shaking frequencies for different trees. However, determining the best shaking frequency and pattern for different sized trees is highly subjective, relying heavily on the operator's experience and trial-and-error, resulting in several unavoidable tree damages. An inexperienced operator may apply extensive stress on the tree, causing tree damage and economic loss. Determining the optimal shaking frequency and pattern is challenging as the optimal parameters vary for each tree and depend on the size of the trunk, mass, leaf density, and branch configuration.

The long-term goal is to increase the efficiency of fruit removal and reduce tree damage by optimizing the shaking parameters for each tree. Some of the objectives of this research are 1) to evaluate the effect of shaking parameters (namely shaking frequency and shaking pattern) on the energy distribution through the tree branches and 2) to optimize the shaking frequency for an individual tree.

Chapter 2

An Experimental Study and Mathematical Modeling of Vibration Transmission in Pistachio Trees

2.1 Introduction

Pistachio production has rapidly expanded in the state of California, and the majority of the acreage is located in the San Joaquin Valley, where over 90% of the U.S. pistachio crop is located (Kallsen, Parfitt, Maranto, & Holtz, 2009). In 2019, California pistachio acreage was 393,595 (288,595 + 105,000, bearing plus un-bearing) acres ("2019 Pistachio Bearing Acreage, Production and Yield Per Acre by District and County, Revised Feb-2020," 2020). Mechanical trunk shaker harvesting machines are very common for harvesting pistachio in California. Since the 1920s, shake-based harvesting machines have been used in the U.S. fruit and nut crops (William, 1923), and trunk shakers have been used since the early 1960s (Affeldt Jr et al., 1989; Horvath & Sitkei, 2001). Although trunk shakers are widely used for harvesting nut trees in California, the efficiency of these machines is still unknown. Therefore, a comprehensive study is required to determine the characteristics of the shaking method that these shakers offer. The methods proposed in this study will provide design engineers with more information about the performance of the machine under field conditions so that improvements of the mechanism or shaking pattern to achieve higher fruit removal during harvest can be made. Improved shaking performance also has the potential to reduce branch breakage, bark and tree damage, tree damage, which often result in a decreased production in subsequent years (Pu, Toudeshki, Ehsani, & Yang, 2018; Pu, Toudeshki, Ehsani, Yang, et al., 2018). Besides, improving shaking performance would increase the energy efficiency of the mechanical trunk shakers, which could result in lower operating costs.

The most significant factor influencing fruit removal during mechanical harvesting is tree structure (Polat et al., 2007). (Láng, 2006) built a dynamic modeling structure of a fruit tree and presented a model of a tree-shaker system based on using an inertial shaker system. Developing a 3D model for an average-sized tree was investigated by several researchers (Hoshyarmanesh, Dastgerdi, Ghodsi, Khandan, & Zareinia, 2017). Moreover, they simulated and studied the effects of shaking frequency, loading type, and loading height on olive-stem-twig joint rupture. (Gupta, Ehsani, & Kim, 2015) presented a methodology to analytically model and optimize different limb prototypes for citrus tree shakers.

Produced acceleration at the fruit joint is one of the important factors influencing fruit removal efficiency. Therefore, (T.-H. Liu, Luo, et al., 2018) measured the density of the green citrus wood and investigated the minimum force needed to remove a fruit at different pulling angles; they also analyzed the acceleration and detachment force at the fruit joint. It is also important to know how the kinetic energy transmits to fruiting branches and causes a force that is greater than the required detachment force on the fruit-stem interface to detach the fruit from the tree. In this regard, Affeldt Jr et al. (1989) measured acceleration with accelerometers and extracted displacements using the linear-variable-differential-transformers technique in the x- and y-directions for cherry tree trunk shakers. Later, (Abdel–Fattah, Shackel, & Slaughter, 2003) collected acceleration data on a commercial shaker and reported a linear relationship between the displacement on the shaker arm and the displacement on the wooden post. (Amirante, Catalano, Giametta, Leone, & Montel, 2007) measured acceleration along the x- and y-axis on the shaker and trunk of an olive tree and displayed the spectrogram of the acceleration for the x-axis of the shaker and the trunk. They also presented the variation pattern of the acceleration vector in the x-y plane during the vibration test. (Catania et al., 2017) measured the acceleration and evaluated the vibrations transmitted to the hand-arm system while using a portable harvester for olive trees. Castro-Garcia et al., (2018) measured acceleration using a triaxial accelerometer inserted inside fruits and analyzed the vibration of the fruit during the fruit detachment process for a canopy shaker for oranges.

(Castro-Garcia, Castillo-Ruiz, Jimenez-Jimenez, Gil-Ribes, & Blanco-Roldan, 2015) found a significant linear relationship between the tree trunk acceleration and the vibration frequency for trunk shaker harvesting of table olives. There was also a significant relationship between the trunk acceleration and shaker head acceleration. Moreover, they have reported that the shaker clamp can affect acceleration transmission from the trunk shaker to the tree trunk depending on its geometry, the characteristics of its rubber pads, and its grabbing pressure. In another study, (Abdel–Fattah et al., 2003) stated that the resulting vibration transmission from the machine to the tree can be determined by a combination of machine design and the characteristics of the tree itself. (T.-H. Liu, Ehsani, Toudeshki, Zou, & Wang, 2017) compared different types of tree shaking tines in a mechanical citrus canopy shaker by an experimental study of the vibrational acceleration spread from the machine to the fruit. The effect of shaking at different parts of the citrus tree was also investigated by using analog accelerometers (T.-H. Liu, Ehsani, Toudeshki, Abbas, & Zou, 2018).

(He, Fu, Karkee, & Zhang, 2017) showed that when using the shaking method, fruit location has a critical influence on apple fruit detachment. Their test results revealed that the amount of acceleration that is transmitted to the fruit was the key factor for fruit detachment during mechanical harvesting. As was expected, fruit that received lower excitation energy during shaking was not detached. It was also found out that the location of fruit within the canopy plays a critical role in the efficiency of the acceleration transmission.

(He et al., 2013) also investigated the energy efficiency of a mechanical harvesting shaker used for cherry harvesting. They determined that the kinetic energy delivered to an excited branch, on average, accounted for 60%, 77%, 92%, and 95% when the input excitation energy was at the respective shaking frequencies of 6, 10, 14, and 18 Hz. Higher shaking frequency resulted in higher total energy delivered to all monitored branches and a higher percentage of input energy distributed to excite the desired branches. In order to quantitatively analyze the capability of the kinetic energy being converted along the tree branches,(Du, Chen, Zhang, Scharf, & Whiting, 2012) set up a sweet cherry tree specimen in the laboratory and defined the relative kinetic energy ratio (RKER).

Knowing more information on the effects of vibration on the tree and fruit could help in the selection of the best-operating conditions and contribute towards enhancing mechanical harvesting machines (Pezzi & Caprara, 2009). Few studies have been conducted on the acceleration response of trees under field conditions, especially for pistachio trees during harvest using a trunk shaker. This chapter focuses on the monitoring 3-D acceleration of pistachio trees and how it varies and transmits from the tree trunk to a branch while the tree is shaken using a commercial pistachio trunk shaker. The objectives of this study were to evaluate the sensor location index (λ), relative force ratio (RFR), and relative kinetic energy ratio (RKER); to find the relationship between acceleration and the sensor location index, and to analyze the trend of RFR and RKER transferred from the trunk to a tree branch for four different trunk shaking patterns.

2.2 Material and Methods

2.2.1 Inertia-Type Trunk Shaker

Field experiments were conducted at a pistachio orchard at Kern County, which is located in the southwest part of the San Joaquin Valley, California. The data were collected in the second week of October 2018. The C7 R-SERIES MK2 CATCHING FRAME SHAKER, which was an inertia-type trunk shaker mechanical harvesting machine, was used in this experiment (shown in Figure 2.1). This machine was made by Custom Orchard Equipment (COE) in the USA. The harvesting machine was equipped with a computerized shaking pattern controller that allowed the operator to define different shaking patterns by controlling and changing the magnitude of shaking intensity and the duration of shaking.

Figure 2.1 The C7 R-SERIES MK2 catching frame shaker by Custom Orchard Equipment was used in this experiment on a pistachio tree

The shaker head was firmly clamped to the trunk at a height of 0.3 m from ground level and the whole tree was shaken. Four different shaking patterns (P1, P2, P3, and P4) were used in this experiment (Figure 2.2). These patterns were what the operator has been using to shake the pistachio trees. In these figures, the x-axis is a shaking time in seconds, and the y-axis is the normalized hydraulic pressure which is produced by the shaker machine during each experiment. The pattern P2 (Figure 2.2 (b)) is similar to pattern P1 (Figure 2.2 (a)); their only difference was in the maximum magnitude at 1 s of shaking time. In P3 (Figure 2.2 (c)), the magnitude is kept constantly at 50% for one second then gradually decreases to 0. Finally, in P4, two-step functions (consecutive vibration patterns) are executed, as shown in Figure 2.2(d). The time of the rising edge and falling edge of the step function are both approximately equal to 28ms. The duration of shaking for each pattern was less than 3 s.

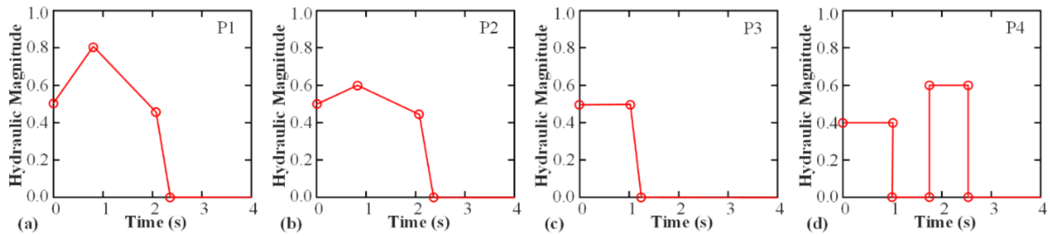


Figure 2.2 Four shaking patterns used in this experiment.

2.2.2 Sensor and Data Logger System

The vibration generated by a shaker head on the trunk can be transferred and distributed across different parts of the tree, including branches, leaves, and fruits. The amount of vibration can be measured in the form of acceleration. Measuring t acceleration can assist in calculating other significant factors that are caused by this vibration, including force, velocity, displacement, and energy. Micro-electromechanical accelerometer sensors can measure acceleration in real-time. Using commercially available accelerometers was not suitable for this project because many of them were not able to tolerate the harsh environment present in the field. Moreover, the system should be able to collect data wirelessly. Using long cables to deliver the electric power from the power supply to the accelerometer and transferring the measured data from the accelerometer to the data logger would not have been practical. Therefore, a new wireless sensor and data logger was designed and built for this experiment Figure 2.3.

The newly designed wireless sensor includes a 3-axis MEMS accelerometer (LIS3DH) and an IEEE 802.11n support 2.4 GHz Wi-Fi (ESP8266EX) which were powered from a 9 V battery. A dustproof and tree branch mountable enclosure was designed and 3D printed to protect the wireless sensor and its battery using a polylactic acid material. The remote data logger for this system was a Raspberry Pi 3 B+ with a 16 GB micro-SD card running Raspbian Stretch Lite (minimal image based on Debian 9 Stretch) operating system which is supplied with a 12 V sealed lead acid generator battery with a capacity of 10 Ah. The wireless sensor was able to communicate with the data logger through a wireless local area network designed for in-field applications. A user-friendly interface was designed for in-field filtering, monitoring, and downloading data.

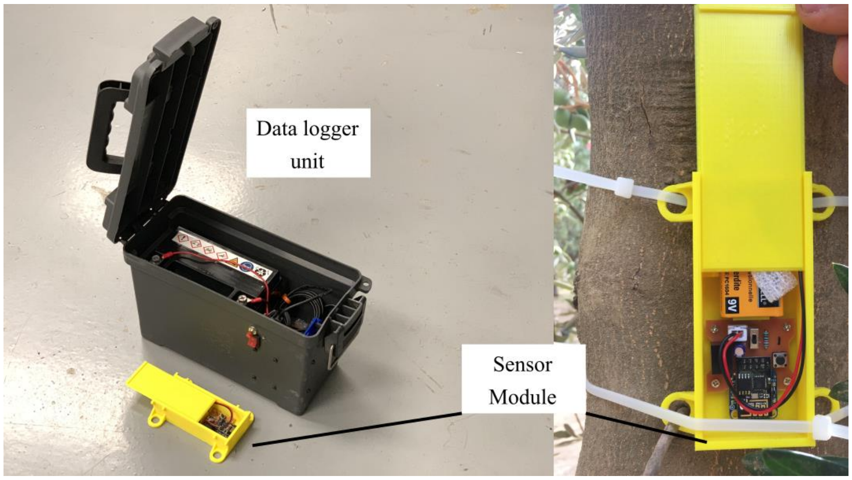


Figure 2.3 Wireless sensor system including data logger unit and multiple sensor modules.

2.2.3 Experimental Setup

A set of wireless accelerometers were installed at different locations throughout the primary, secondary, and tertiary branches of each tree to acquire acceleration responses to input excitations. The vibratory excitations generated from the shaker head of the shaker were applied perpendicularly to the trunk. As shown in Figure 2.4, three adjacent pistachio trees with different sizes and shapes were chosen for the experiments.

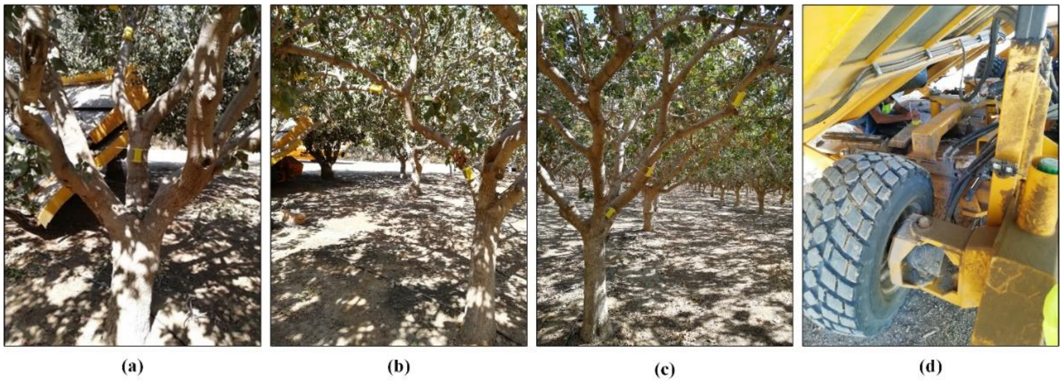


Figure 2.4 Accelerometers installed on (a) tree I, (b) tree II, (c) tree III, and (d) the shaking axle of the shaker.

A total of ten wireless accelerometers were used in this experiment, one was installed on the shaker head, which was labeled as S10 for the first tree, S20 for the second tree, and S30 for the third tree in Figure 2.5. The other nine sensors were installed on the three trees, on the first branch, middle branch, and top branch of the tree; the locations were named S_{tb}, where t is the tree number (from 1 to 3) and b is the branch number (from 1 to 3) on which the accelerometer was installed.

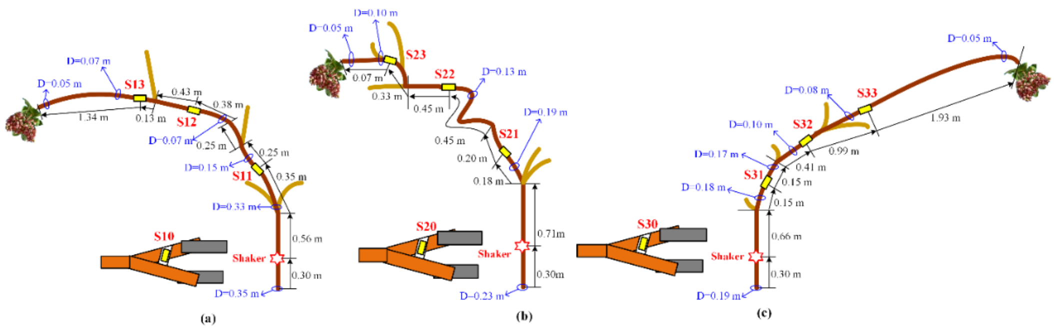


Figure 2.5 The location of sensors (yellow boxes) on the shaker head (orange color) and first, second, and third branches (brown color) of (a) tree I, (b) tree II, and (c) tree III.

Any vibration can be detected and measured by these accelerometers and immediately transferred to the remote data server through the in-field local wireless network. The total mass of the wireless accelerometer sensor, battery, and the housing was 98 grams. The orthogonal axes of a LIS3DH accelerometer are shown in Figure 2.6(a). The orientation of the accelerometer installed on the shaker head of the machine is shown in Figure 2.6(b), and the placement of the accelerometer on the branch of the tree is shown in Figure 2.6(c). In all sensor installations, a_x and a_y are parallel with the surface of the x-y plane of the vibrated object, and a_z is perpendicular to this plane.

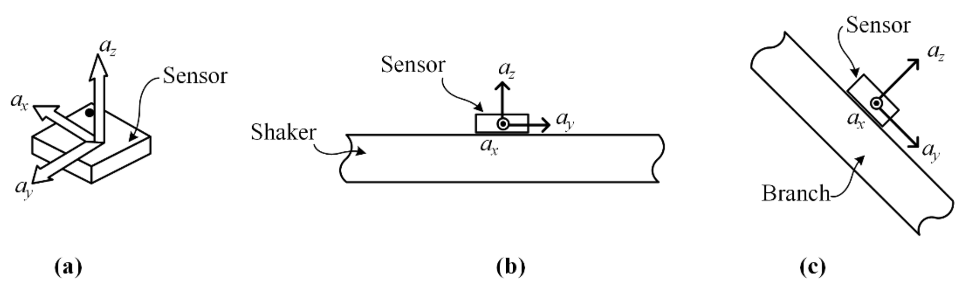


Figure 2.6 The directions of acceleration (a) on the sensor, (b) the machine and (c) a branch, in the Cartesian coordinate system

Due to practical limitations, it is assumed that the acceleration of the trunk at the clamped point is the same as the acceleration on the shaker head. In this case, the directions of measured acceleration on the trunk are similar to those shown in Figure 2.6(b). The frequency weighted root mean square acceleration was evaluated for each axis, and the acceleration resultant a_r, in $m \cdot s^{-2}$, was obtained by equation (2.1) (T.-H. Liu et al., 2017; Pu, Toudeshki, Ehsani, Yang, et al., 2018).

$$|a_r| = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{2.1}$$

where a_x, a_y and a_z are acceleration in x, y and z direction.

2.2.4 Sensor Location Index

The sensor location index was used for the first time by (He et al., 2017). In this study, the sensor location index (λ) for each sensor is defined by equation (2.2). This index represents the sum of the ratio of length to diameter from the shaking point at the trunk of the tree to the location of the sensor installed.

$$\lambda = \sum_{i=1}^{n} \frac{L_i}{D_i} \tag{2.2}$$

where L_i in m is the distance of the sensor from the shaking point or last bifurcation point, and D_i in m is the average diameter of the trunk or branch at the sensor location. The subscript i represents the trunk, first branch, second branch, and so on. It is important to highlight that unlike (He et al., 2017), the $\frac{D}{L}$ equation was not used because of the D is never equal to the zero for the trunk and branch of the tree, but L can be equal to zero. Therefore, based on equation (2.2), in this study, λ increases as distance increases from the shaking clamped point.

2.2.5 Force and Vibration Transmission

To derive the relative force ratio (RFR), it is assumed that the density (ρ) of the trunk and branch is uniform. By knowing the force F and mass m, equation (2.3) can be written as:

$$\begin{cases} F_i = m_i a_i \\ m_i = \rho V_i \\ V_i = \pi \left(\frac{D_i}{2}\right)^2 \end{cases} \tag{2.3}$$

where V is the volume of a unit length trunk or branch and i is the number of the sensor location. Then, the force of a unit length trunk or branch at a location can be calculated by equation (2.4):

$$F_i = \frac{1}{4}\pi\rho D_i^2 a_i \tag{2.4}$$

The RFR is defined by equation (2.5) to represent force level changes at a specific sensor location i in comparison to a reference point j along the transmission path:

$$\mathrm{RFR}_{ij} = \frac{F_i}{F_j} = \frac{D_i^2 a_i}{D_j^2 a_j} \tag{2.5}$$

By setting the excitation point at the reference position, RFR could be used to calculate the force of any other locations relevant to the excitation point.

2.2.6 Kinetic Energy Transmission and Variation

The relative kinetic energy ration (RKER) that represents energy level changes at monitoring location i and j along a transmission path was defined by (Du et al., 2012) as shown in equation (2.6):

$$\mathrm{RKER}_{ij} = \frac{E_i}{E_j} = \left(\frac{D_i v_i}{D_j v_j}\right)^2 \tag{2.6}$$

where E is the kinetic energy of a unit length branch at the monitored location, D is the diameter of the branch, and v is the velocity, which can be obtained from the integration of the acceleration. Hence, by assuming that the density ρ of the trunk and branch is uniform, E_i can be calculated from equation (2.7):

$$E_i = \frac{1}{2}m_i v_i^2 = \frac{1}{8}\pi\rho D_i^2 v_i^2 \tag{2.7}$$

In this chapter, the maximum velocity response is used to calculate RKER for each shaking pattern by using equation (2.6).

2.3 Results and Discussion

2.3.1 Acceleration Throughout the Shaking Process

As an example, the 3-axis x, y, and z components of the accelerations (a_x, a_y, and a_z) and the acceleration resultant (a_r) for the tree I were measured from accelerometer S10 and accelerometer S13 and are plotted in Figure 2.7(e-l) under four different excitation patterns (other trees are not shown).

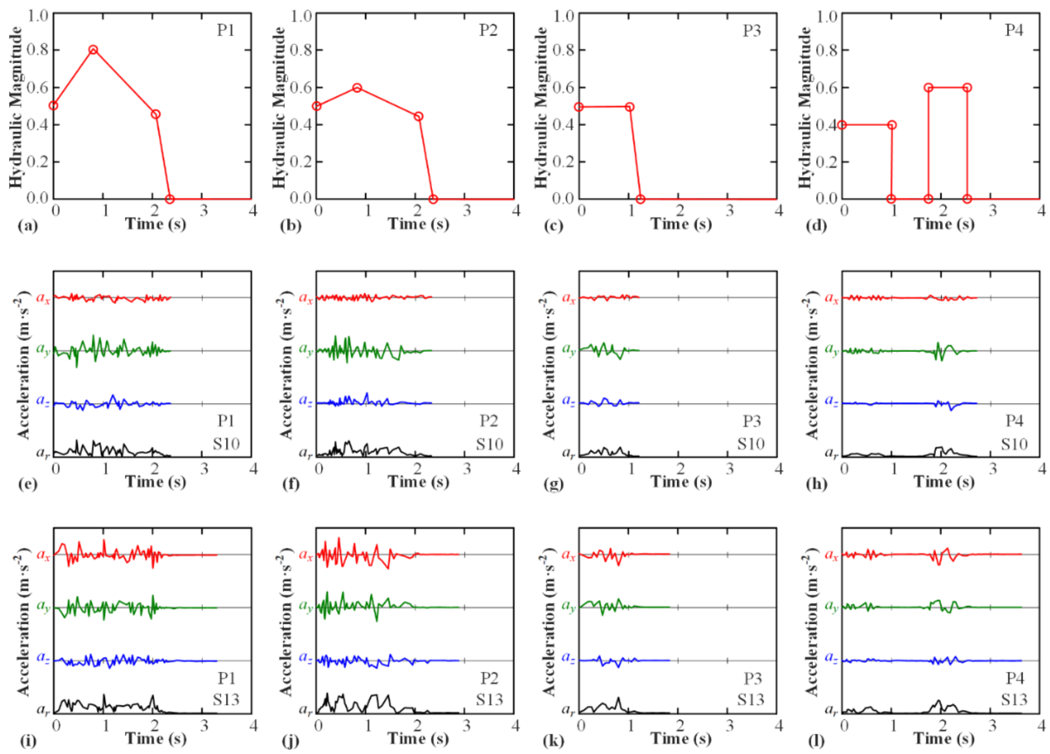


Figure 2.7 Shaking patterns (a) P1, (b) P2, (c) P3, and (d) P4; generated acceleration in three axes measured by sensor S10 installed on the shaker by shaking pattern (e) P1, (f) P2, (g) P3, and (h) P4; and the received acceleration measured in three axes by sensor S13 installed on the third branch of the tree I by shaking pattern (i) P1, (j) P2, (k) P3, and (l) P4.

2.3.2 The Acceleration Trend in Trees

The magnitude variation of acceleration (3 components and resultant) for all sensors installed on three trees (see Figure 2.5) shaken with four different shaking patterns are shown in Fig. 6. It is found that the shaking pattern affects the amount of transmitted acceleration to the last sensor installed on the branches with the longest distance from the source of the shake.

Figure 2.8 shows the measured acceleration of every sensor in each individual axis using all shaking patterns. Figure 2.8 (d), (h) and (l) shows the resultant acceleration of each tree. It can be seen that all patterns and trees (except pattern 2 tree one and pattern 4 tree three) acceleration measured in the last sensor is lower than the previous sensor. The fact that the measured acceleration trend is different in tree one and three using different patterns shows shaking patterns can affect the vibration transmission in a tree.

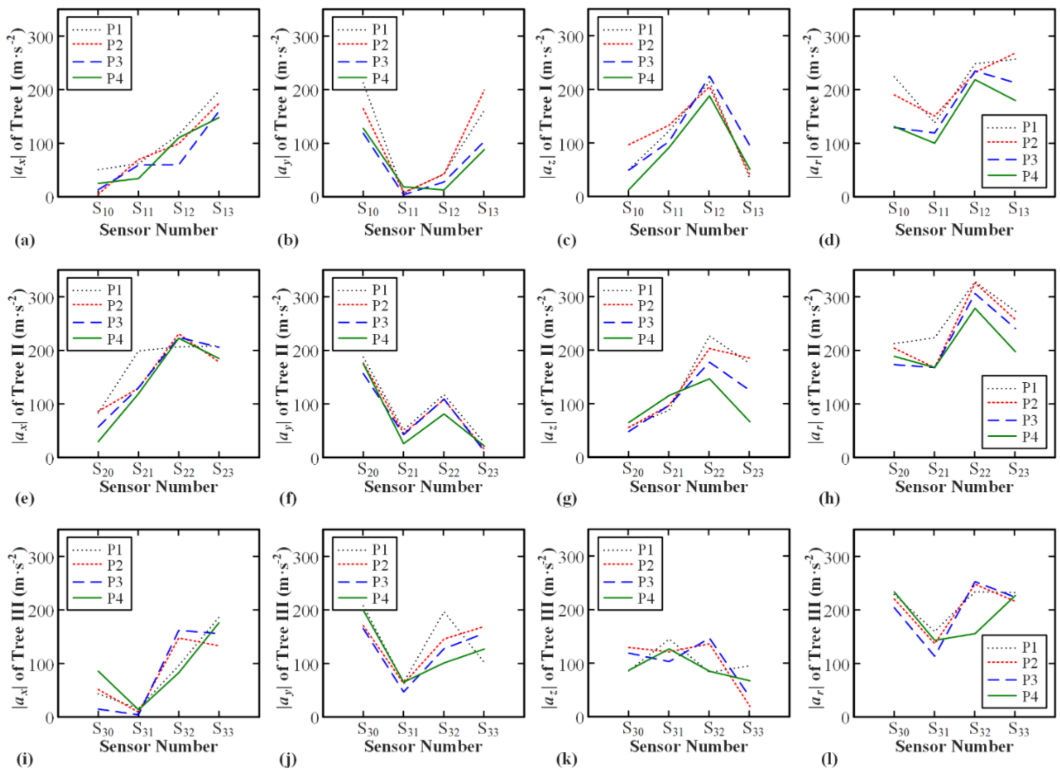
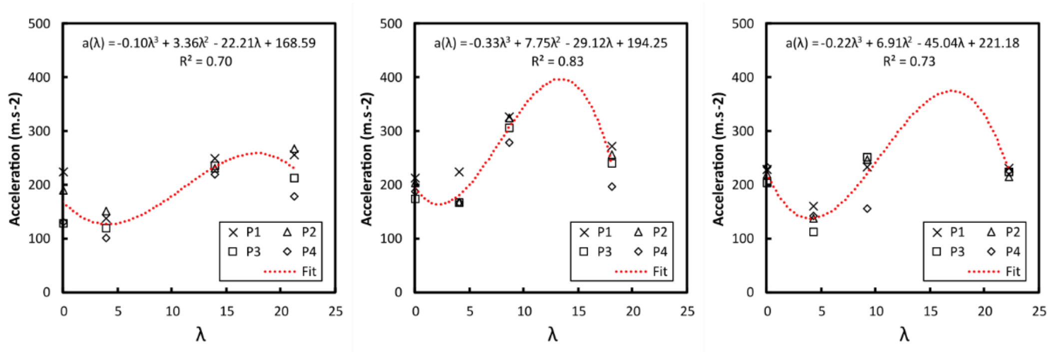


Figure 2.8 Acceleration magnitude changes from the shaking clamp point to the end of the top branch of the shaken trees (a-d) tree I, (e-h) tree II and (i-l) tree III.

2.3.3 Models of the Changing Trend of Acceleration

Based on the results of Figure 2.8, it is found that the tree varieties, morphology, and structure are the most significant factors influencing the changes of acceleration, which could potentially affect the fruit removal rate. These differences will give different results for the transmission of acceleration, force, and energy. Nevertheless, the relationship between the peak values of acceleration with λ is shown in Figure 2.9.



(a) (b) (c)

Figure 2.9 The relationship between the acceleration of the sensor and λ in (a) tree I, (b) tree II, and (c) tree III

From Figure 2.9, it can be seen that the relationship between the peak values of acceleration resultant with the sensor location index shows similar results under four different shaking patterns for three different trees. As a result, the changes in acceleration as a function of λ can be mathematically modeled with a third-order polynomial equation (2.8).

$$a(\lambda) = \sum_{k=0}^{3} c_k \lambda^k \qquad (2.8)$$

where c_k is the coefficient of the function and its values are changed depending on the morphology of the tree.

2.3.4 Force and Kinetic Energy Transmission Trends

The variation and transmission of the RFR can be calculated using equation (2.5) from the shaking point to each sensor location index λ. The results of the relative force ratio versus λ for the four different shaking patterns in three trees are shown in Figure 2.10. In general, as can be observed in this figure, the RFR was decreased when the λ increased. However, the decrease rate was different for different patterns. As a result, by considering the mass of the tree, the best pattern that could transfer higher force to the last branch was P3 for all three trees. Surprisingly, it is found that it is not necessary to apply a long time shaking (see Figure 2.7(a), (b) and (d)) to transfer a high amount of force to the last branch; a small shock (Figure 2.7(c)) achieved efficient vibration transmission to the last branch without causing much damage to the bark of the tree trunk.

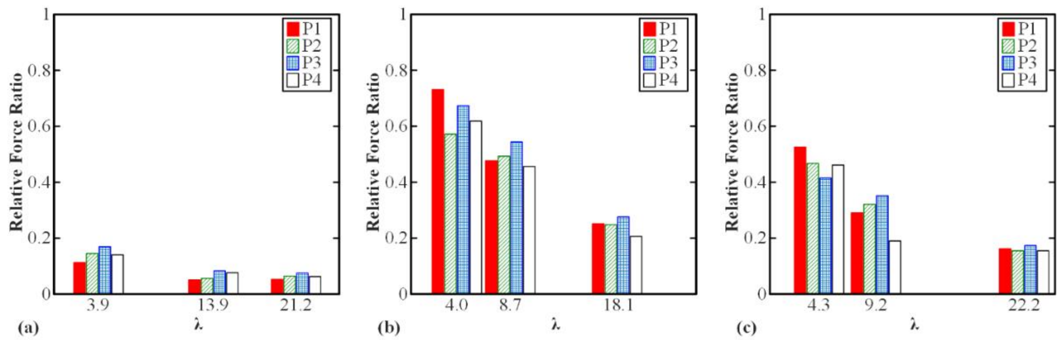


Figure 2.10 The relationship between the relative force ratio and λ for different shaking patterns in (a) tree I, (b) tree II, and (c) tree III

The variation and transmission of the RKER can be calculated using Equation (2.6) from the shaking point to each sensor location index λ. The results of the relative kinetic energy ratio versus λ for the four different shaking patterns in three trees are shown in Figure 2.11. Based on this result, it is found that the higher rate of the kinetic energy which was transferred to the last branch was pattern P2 in the tree I, P1, and after that P2 in tree II, and P3 and after that P2 in tree III.

Moreover, it is found the shape and age of the tree influence the result, and these morphological matters cause more complexity to the system. This complexity is shown as fluctuations in the values of the RKER, which has an unknown correlation with λ. The values of RKER of the tree I are less than one and much smaller than those of the other two trees. Hence, more energy is needed to harvest nuts from larger pistachio trees because of the large branches can absorb more energy and cause more damping of force and kinetic energy transmission.

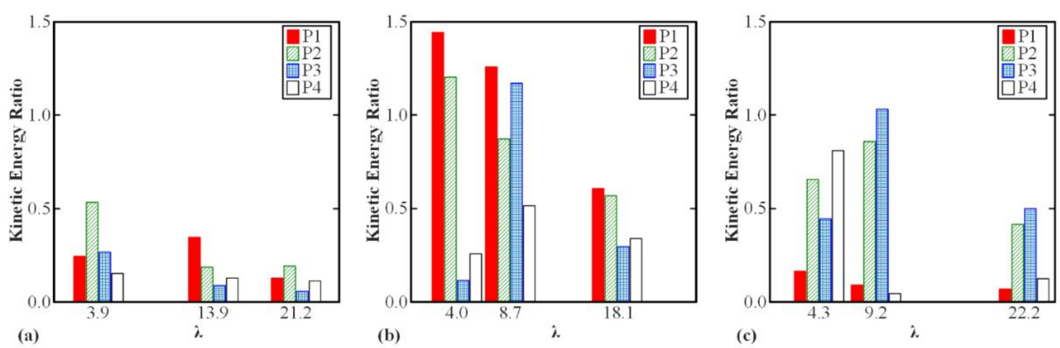


Figure 2.11 The relationship between the kinetic energy ratio and λ for different shaking patterns in (a) tree I, (b) tree II, and (c) tree III

Finally, this is important to highlight that finding the optimum shaking pattern by considering the acceleration alone is not enough. It requires the study of other parameters, including tree morphology, shaking velocity, displacement, and mass. The introduced sensor location index, λ, can assist in clarifying and estimating how far the shaking energy can be transferred and how much the generated force was damped as a function of λ using different shaking pattern.

2.4 Conclusion

In this chapter, the effects of four different shaking patterns on three pistachio trees of different ages, shapes, and sizes were investigated in the field. The vibration acceleration of the real pistachio tree was measured using a wireless network of 3-axis accelerometers installed on different parts of the trees and shaker head during the shaking harvest. Changes of acceleration and the effect of tree morphology on the magnitude of acceleration in each pattern are presented and discussed. A new location index λ, which is based on the distance of the sensor from the shaking point and diameter of the branch at each sensor location, is introduced. It was found out that a third-order polynomial function can be suitable for mathematical modeling of the resultant acceleration magnitude as a function of λ. Moreover, the RFR and RKER at the sensor location index of λ are calculated and the results are presented for each shaking pattern and shaken tree. It was found that the RFR decreases as the λ increases and the decrease rate is different at different shaking patterns. The changes of RKER are complicated and influenced by other parameters such as the size and shape of the tree morphology and the shaking patterns. But, based on the calculated results of the transmitted RFR and RKER, it can be concluded that a larger pistachio tree needs more energy to be harvested by using an inertia-type trunk shaker.

Chapter 3

Finding Proper Shaking Parameters for Pistachio Trees

3.1 Introduction

Pistachio nuts are great candidates for mechanical harvesting due to their hard shell and unique shape of the fruit. Trunk shaking is the most common mechanical harvesting system for pistachios. Since the emergence of trunk shakers in the late 1970s, there has not been a significant change in the vibration generating system and most of the current trunk shakers perform on a pre-programmed shaking pattern. To the best of our knowledge, there is no study on the vibration energy transmission for the pistachio tree canopy. The main objectives of this study were a) to evaluate the effect of tree morphology and shaking parameters such as tree size, canopy shape, and shaking pattern on the energy distribution through the branches and b) to optimize the shaking intensity for individual pistachio trees based on a tree-specific feedback loop. A set of wireless 3D accelerometer sensor system was built and used to monitor the vibration transmission through the tree canopy at three different locations in the tree canopy to monitor the energy transmission between the machine shaker head and the tree trunk. Thirty trees were selected for this experiment and were divided into three groups based on the trunk circumference size. To study the effect of a shake pattern on the vibration transmission through the tree, four shake patterns were selected and tested. The actual shake duration was measured and showed an average of 30% longer time compared to the shake pattern duration. The effect of all four shake patterns was analyzed using continuous wavelet transform. Tree's responses were analyzed and the optimum shaking intensity for each tree was determined. A model was developed to estimate the optimum shaking intensity for pistachio trees based on their trunk size. The model showed %37, %57, and %65 is the optimum shaking intensity for small, medium, and large trees, respectively.

Tree nuts (such as pistachios) are good candidates for mechanical harvesting due to their hard shell and physical properties of the tree (Polat et al., 2007). From an economic point of view, pistachio is one of the most valuable agricultural products in the United States. The U.S. is the second pistachio producer in the world, producing more than 200,000 metric tons of pistachio ("World Pistachio Report," 2019) with a monetary value of $300 million in 2017 ("Pistachio trade, Top importing countries of pistachios," 2018). The majority of the U.S. pistachios are produced in California and are harvested mechanically. A high-yield pistachio production in California requires 1150 mm per ha water (Marino et al., 2018). Thus, a more efficient harvesting system will reduce the fruit loss and indirectly reduce the water used to produce 1 kg product. Commercial trunk shakers and catching frames have been adapted for pistachio harvesting and are widely used in California. Mechanical harvesting is less common in other major pistachio producer countries (such as Iran and Turkey), and very few mechanical harvesting studies had been done in these countries (Loghavi & Rahimi, 2007; Polat, Acar, Bilim, Saglam, & Erol, 2011; Polat et al., 2007).

Trunk shakers have not been significantly modified since the late 1970s (Afsah-Hejri et al., 2021). Most commercially available trunk shakers allow the operator to adjust the shaking frequency manually. Researchers performed tests on pistachio, almond and other nut trees using both trunk and limb shakers. Trunk shaking is the suggested shaking method for large-size pistachio trees with the following conditions: amplitude of 40–60 mm and frequency between and 15–25 Hz (Polat et al., 2007). (Polat et al., 2007) studied some of the parameters that affected the detachment of the fruit. Although they achieved a 100% fruit removal at the frequency of 20 Hz and amplitude of 60 mm, they did not recommend these conditions for pistachio harvesting due to the excessive vibration of the frame at high amplitudes. Therefore, they suggested shaking medium-size pistachio trees with an inertia-type limb shaker at 20 Hz and amplitude of 50 mm.

A larger trunk size decreases kinetic energy transmission from the shaker to the canopy surface. Earlier studies in California showed that the final harvester efficiency was decreased by 30%, associated with increasing trunk circumference more than 1.27 m (L. Ferguson, Glozer, Reyes, Rosa, & Castro-Garcia, 2014). Proper pruning can increase the efficiency of harvest and a well-pruned orchard (trees with similar characteristics) may make the harvesting more efficient.

The vibration transmissions across olive and citrus trees were simulated using general kinematic and numerical models or the finite element method (Bentaher, Haddar, Fakhfakh, & Mâalej, 2013; Gupta, Ehsani, & Kim, 2016; Hoshyarmanesh et al., 2017; S. Savary, Ehsani, Schueller, & Rajaraman, 2010). However, these general techniques cannot be applied to all shapes of trees due to the various tree morphology. Therefore, there is a need for another technique to monitor the vibration transmission across the tree. The Newton's second law of motion (Liu, 2019; Tombesi et al., 2017) simply describes the amount of force that is proportional to the acceleration of the object. Thus, measuring the acceleration in each point of a moving object is a good indicator for measuring the relative force at that point. There have been multiple studies in which accelerometers was used at different parts of the tree to a) evaluate the effectiveness of shakers (Bi et al., 2013; Dumont & Kinsley, 2015; Liu et al., 2017; Pu, Toudeshki, Ehsani, & Yang, 2018; Tombesi et al., 2017) and b) to measure the tree damage (Liu et al., 2018; Pu, Toudeshki, Ehsani, Yang, et al., 2018).

Current shakers can create different shaking patterns by changing shaking intensity vs. time. These patterns can be programmed into the shaker's computer control system. This allows the operator to adjust the shaking frequencies for different trees. However, determining the best shaking frequency and pattern for different sized trees is highly subjective, relying heavily on the operator's experience and trial-and-error, resulting in several unavoidable tree damages. An inexperienced operator may apply extensive stress on the tree, causing tree damage and economic loss. Determining the optimal shaking frequency and pattern is challenging as the optimal parameters vary for each tree and depend on the size of the trunk, mass, leaf density, and branch configuration.

The long-term goal of this study is to increase the efficiency of fruit removal and reduce tree damage by optimizing the shaking parameters for each tree based on its size and canopy characteristics. The specific goal was 1) to evaluate the effect of shaking parameters (namely shaking frequency and shaking pattern) on the energy distribution through the tree branches and 2) to optimize the shaking frequency for individual pistachio trees based on their trunk size.

3.2 Theoretical Model

The most common vibration generating systems work by rotating an eccentric mass around a single point in a plane. Most commercial trunk shakers use either one or two eccentric rotating masses to generate the required oscillatory force for harvesting fruits. Figure 3.1 shows the main components of this mechanism. The dynamic equation of motion of this system is shown by Equation (**3.1**) (Láng, 2006; Rao, 2011)

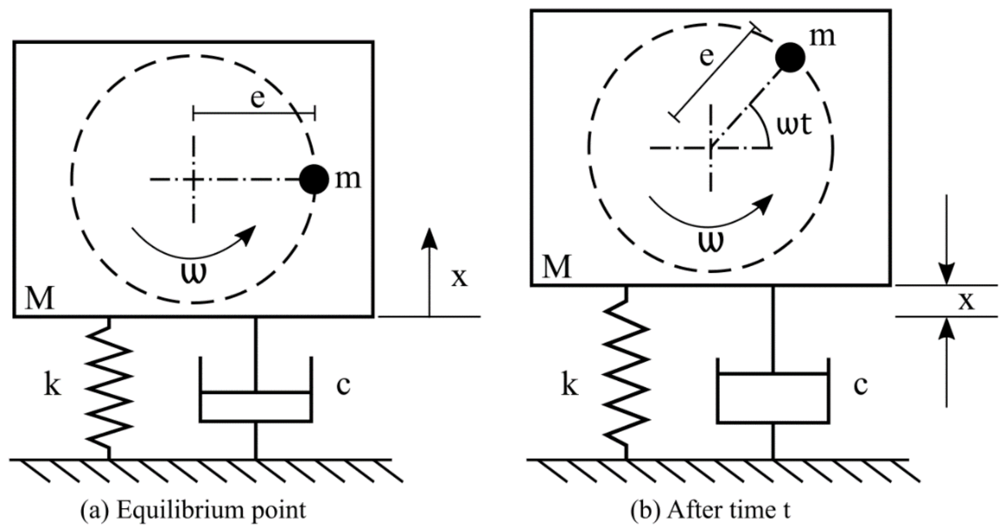


Figure 3.1 Eccentric rotating mass m generates oscillatory force and movement in mass M.

$$M\ddot{x} + c\dot{x} + kx = (me\omega^2)\sin\omega t \qquad (3.1)$$

where *m* is rotating mass (kg), *e* is the eccentricity of mass *m* (m), ω is rotational speed ($rad.s^{-1}$), *k* and *c* are stiffness and damping of the system respectively ($N.m^{-1}$) and ($N.s.m^{-1}$), *M* is total mass affected by an oscillatory force which includes eccentric mass *m*, the mass of shaker head and the portion of tree mass when the shaker is attached to a tree and *x* is the displacement of mass *M*.

The solution of the differential equation (3.1) has two terms.

$$x = x_c + x_p \qquad (3.2)$$

The transient response (complementary function, x_c) and steady state response (particular solution, x_p). As the transient response decays quickly the important part of the solution is the steady-state term. The general form of steady-state response of the system is:

$$
\begin{aligned}
x(t) &= X_0 \sin(\omega t - \phi) \\
\dot{x}(t) &= X_0 \omega \cos(\omega t - \phi) \\
\ddot{x}(t) &= -X_0 \omega^2 \sin(\omega t - \phi)
\end{aligned}
\tag{3.3}
$$

Now if we subsidize equation (3.3) into equation (**3.1**), we get:

$$
\begin{gathered}
M(-X_0\omega^2 \sin(\omega t - \phi)) + c(X_0\omega \cos(\omega t - \phi)) \\
+k(X_0 \sin(\omega t - \phi)) = (me\omega^2) \sin \omega t
\end{gathered}
\tag{3.4}
$$

Organizing the terms in the above equation, we get:

$$
\begin{gathered}
X_0[(k - M\omega^2) \sin(\omega t - \phi) + c\omega \cos(\omega t - \phi)] \\
= (me\omega^2) \sin \omega t
\end{gathered}
\tag{3.5}
$$

Using compound-angle equations, we can decompose the equation above to:

$$
\begin{gathered}
X_0[(k - M\omega^2)(\sin \omega t \cos \phi - \cos \omega t \sin \phi \\
+c\omega(\cos \omega t \cos \phi + \sin \omega t \sin \phi)] = (me\omega^2) \sin \omega t
\end{gathered}
\tag{3.6}
$$

Factoring out the $\sin \omega t$ and $\cos \omega t$ terms result in:

$$
\begin{gathered}
X_0 \sin \omega t\, [(k - M\omega^2) \cos \phi + c\omega \sin \phi] \\
+ X_0 \cos \omega t\, [-(k - M\omega^2) \sin \phi + c\omega \cos \phi] \\
= (me\omega^2) \sin \omega t
\end{gathered}
\tag{3.7}
$$

Coefficients of $\sin \omega t$ and $\cos \omega t$ on the left-hand side of the equation should be equal to the right-hand side terms.

$$
\begin{cases}
X_0[-(k - M\omega^2) \sin \phi + c\omega \cos \phi] = 0 & (a) \\
X_0[(k - M\omega^2) \cos \phi + c\omega \sin \phi] = me\omega^2 & (b)
\end{cases}
\tag{3.8}
$$

Phase angel (ϕ) can be calculated from equation (3.8a).

$$
\tan \phi = \frac{c\omega}{k - M\omega^2} \quad \rightarrow \quad \phi = \tan^{-1} \frac{c\omega}{k - M\omega^2}
\tag{3.9}
$$

The amplitude of steady-state response X_0 can be calculated as

$$
\begin{gathered}
{X_0}^2[(k - M\omega^2)^2 \sin \phi^2 + (c\omega)^2 \cos \phi^2 \\
-2c\omega(k - M\omega^2) \sin \phi \cos \phi + \cos \phi^2\, (k - M\omega^2)^2 \\
+(c\omega)^2 \sin \phi^2 + 2c\omega(k - M\omega^2) \sin \phi \cos \phi] = (me\omega^2)^2
\end{gathered}
\tag{3.10}
$$

Then,

$$
{X_0}^2[(k - M\omega^2)^2 + (c\omega)^2] = (me\omega^2)^2
\tag{3.11}
$$

$$X_0 = \frac{me\omega^2}{\sqrt{(k - M\omega^2)^2 + (c\omega)^2}} = \frac{me(\frac{\omega}{\omega_n})^2}{M\sqrt{(1 - (\frac{\omega}{\omega_n})^2)^2 + (2\zeta\frac{\omega}{\omega_n})^2}} \quad (3.12)$$

Equation (3.12) shows the amplitude of the steady-state response of the system and the total steady-state response of the system is shown in equation **(**3.13). Equation (3.14) shows the amplitude of force generated by the rotating mass.

$$X = \frac{me(\frac{\omega}{\omega_n})^2}{M\sqrt{(1 - (\frac{\omega}{\omega_n})^2)^2 + (2\zeta\frac{\omega}{\omega_n})^2}}\sin(\omega t - \phi) \quad (3.13)$$

$$F_0 = me\omega^2 \quad (3.14)$$

where ω_n is the natural frequency of the system and ζ is the damping ratio of the system, which both are determined by mechanical properties of systems naming mass, stiffness, and damping. After a mechanical shaker is built, all the parameters in equation **(**3.13) are fixed except ω. The angular velocity of the eccentric mass is usually generated by a hydraulic motor. The flow rate of hydraulic oil through the motor will control angular velocity. Figure 3.2 shows how the force and response of the system are affected by angular velocity ω. A higher angular velocity will not necessarily result in a more efficient harvest. Increasing ω will increase the displacement of the tree, but after a certain point increasing ω will result in a decrease of displacement, which is not in favor of a good fruit removal. This critical point is located at different frequencies for each tree. A higher ω will also result in

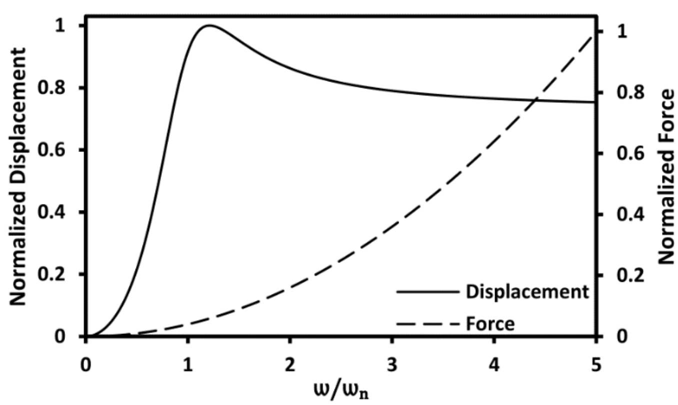


Figure 3.2 Normalized displacement and force vs. excitation frequency ratio (ω/ωn)

an excessive force on the tree. The trunk of the tree can be damaged by this excessive force and can reduce the following year's fruit yield (Gupta et al., 2016). Shaking frequency is defined in equation (3.15).

$$F = \frac{\omega}{2\pi} \qquad (3.15)$$

where F is shaking frequency (Hz) and ω is the angular velocity (rad/s). This equation shows angular velocity and shaking frequency are linearly proportional. Thus, it is very important to find proper shaking frequency for each tree to have an efficient harvest; and not applying excessive force to the tree.

3.3 Materials and Methods

3.3.1 Tree Selection

A series of field tests were conducted at a pistachio orchard in Lost Hills, CA, on the 1st week of September 2019. Three groups of trees were categorized based on their trunk circumference size. The first group, small circumference less than 63 cm, second group, medium circumference between 63 cm and 95 cm, and third group, large circumference greater than 95 cm. These sizes were selected so that trunk diameter would be less than 20 cm for small, between 20 cm and 30 cm for medium, and greater than 30 cm for large trees. Ten trees were selected for each group resulting in a total of thirty trees for this experiment. Figure 3.3 shows the distribution of selected pistachio trees based on their trunk circumference size.

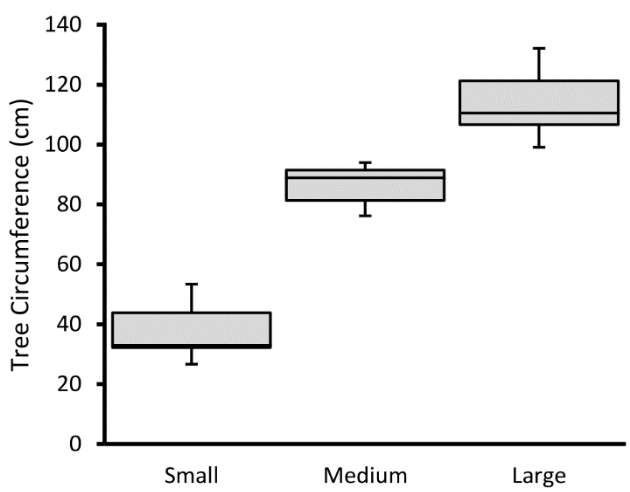


Figure 3.3 Distribution of pistachio trees based on their circumference. Ten trees (n=10) were selected in each size category

3.3.2 Shaking Machine and Shaking Patterns

A trunk shaker machine (model 2018-C7R) built by COE; USA was used in this experiment. This machine had a central control computer system that controlled all steps in the shaking sequences. This computer could be programmed to generate shake patterns designed by the operator. Therefore, four shaking patterns were selected (Figure 3.4) to test and determine the optimal shaking frequency for trees with different trunk sizes. The shaking patterns included two types of standard input: ramp (Figure 3.4, pattern 1, and 4) and step input (Figure 3.4, pattern 2). Pattern 1 started at 20% intensity and increased to 40% in 3 seconds. In pattern 2 a steady shaking at 50% was applied to the tree for 3 seconds. Pattern 3 was a pattern used by the operator which started at 54%, increased to 75% in 1 second and then decreased to 44% at 2.75 seconds and went to zero by the time of 3 seconds. Patterns 1,2 and 3 were used to shake medium and large trees. Pattern 4 was designed for small trees, which started at 25% and increased to 40% by 1.5 seconds. Actual shake duration was measured and compared to four patterns durations.

Based on the recommendation of the field manager, the maximum intensity of these patterns was chosen to avoid damage to the trees and shaker machine. Small size trees were shaken twice using pattern 4. Medium and large trees were shaken four times using patterns 1, 2, and 3. Moreover, the tree sizes and shake patterns used for each category are shown in Table 3.1. The maximum weight loss of a tree is attributed to its first shake, which might change the vibration transmission. Thus, in this study, the first two shakes of each tree have been done with the same pattern.

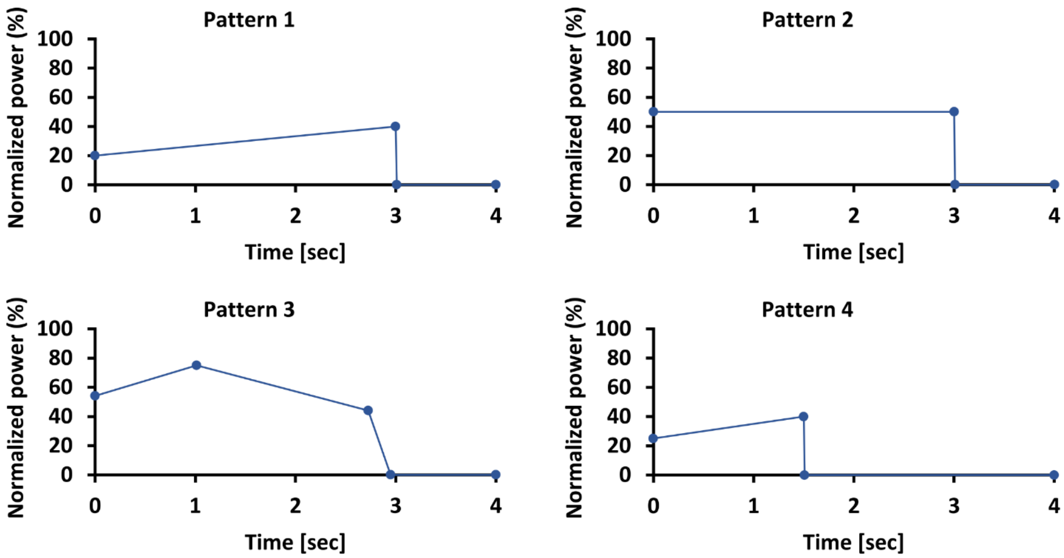


Figure 3.4 Shake patterns used to collect data for this experiment. Patterns 1,2 and 3 were used to shake the medium and large size trees and pattern 4 was used for the small trees.

Table 3.1 Tree sizes and shake patterns used for each category

	Small	Medium	Large
Circumference	< 63 cm	63 – 95 cm	> 95 cm
Equivalent Diameter	< 20 cm	20 – 30 cm	> 30 cm
Shake 1	Pattern 4	Pattern 1	Pattern 1
Shake 2	Pattern 4	Pattern 1	Pattern 1
Shake 3	———	Pattern 2	Pattern 2
Shake 4	———	Pattern 3	Pattern 3

3.3.3 Wireless Sensor System

Wired accelerometer sensors have been previously used to evaluate the efficiency of harvesters on citric trees (Liu et al., 2017, 2018; Pu, Toudeshki, Ehsani, & Yang, 2018; Pu, Toudeshki, Ehsani, Yang, et al., 2018). Despite the promising results from this type of accelerometer sensor, the installation process of the wired sensors in the field would not be feasible and would slow down the in-situ data collection process. Therefore, a network of new wireless sensor systems was designed and built to measure and record the acceleration transferred to different parts of the tree. The system consisted of a control and triggering unit, a wireless router, and multiple wireless sensors. Each wireless sensor module includes a built-in micro-electromechanical system (MEMS) digital output motion sensor, which is an ultra-low-power high-performance 3-axis "nano" accelerometer (LIS3DH STMicroelectronics) set to ± 16g, a wireless module (ESP8266MOD developed by Ai-Thinker Technology), storage unit (Adafruit 5V ready Micro-SD Breakout board+) which are all powered by a 9-volt battery (Figure 3.5 a). The hub of the network included a TP-link 300 Mbps Wireless N router (TL-WR841N), a Raspberry Pi 3A+ which ran an in-house software on the Raspbian Buster Lite

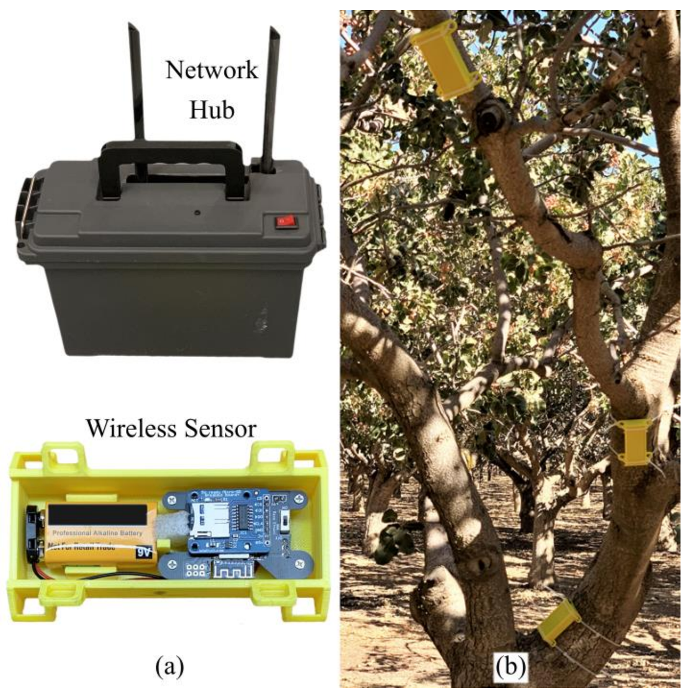


Figure 3.5 (a) Wireless accelerometer sensor system consisting of multiple wireless sensors and one network hub unit, (b) Three wireless sensor were attached to the tree to record vibration.

operating system, a DC-DC converter, and a 12-volt dry cell battery pack to power them up. The 300 Mbps baud rate of the wireless router was sufficient to allow stable access to all connected 32 wireless devices in the network at the same time during the in-situ experiment. The wireless module of each sensor was set on receiver mode only to maximize the reaction response of the sensor to every triggering signal and record more synchronized data together with other triggered sensors.

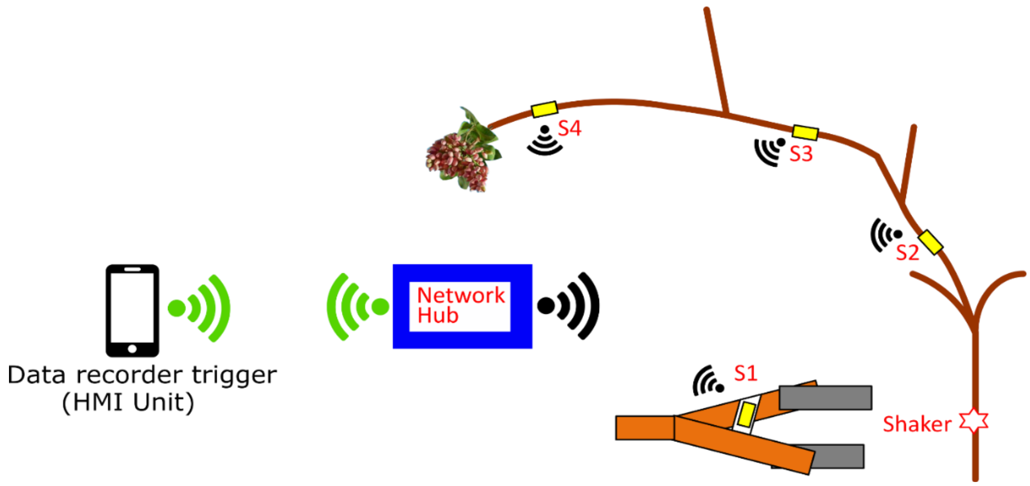


Figure 3.6 Wireless sensor system components and connections.

These sensors recorded acceleration in x, y, and z-axis; and in the unit of $m.s^{-2}$. They were capable of recording up to 550 samples per second or one sample every 1.82ms in each axis. Each sensor was connected to the network hub and was wirelessly triggered to record data at the highest possible sampling rate and turned OFF after the turning OFF time that was defined inside the received triggering signal package. The number of active sensors needed for each experiment was selected using any ordinary web browser on a smartphone/tablet/computer which was connected to the local wireless network. A local webserver was developed for this project on a Raspberry Pi computer to handle the adjustable setting and communication between the smartphone/tablet/computer and all sensors in the local network. Figure 3.6 shows the general diagram of the in-field experimental setup for the wireless system network. In this experiment, one sensor was attached to the shaker head, and three sensors were attached to each tree.

3.3.4 Frequency Analysis Method

To analyze the vibration data recorded by accelerometer sensors, continuous wavelet transform (CWT) was used in MATLAB 2019a. Unlike Fourier transform in which time-domain information will be lost in the frequency domain, CWT allows finding the frequency component of a signal localized in the time domain. This helps to simply analyze the oscillation waveforms which their fundamental frequencies are varying over time. The wavelet corresponding to scale a and time location b is shown in Equation (3.16) (Sinha, Routh, Anno, & Castagna, 2005).

$$\psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\psi(\frac{t-b}{a}) \tag{3.16}$$

where $\psi(t)$ is principal wavelet defined $\psi(t) \in \Re^2$ with zero mean, a is a positive scale and b is representing the shift in the time domain. An Analytic Morse Wavelet with the symmetry equal to three and the time-bandwidth equal to 60 were used to extract tree response frequency components during a shake (Lilly & Olhede, 2012).

Normalized peak time (T_n) is defined by equation (3.17):

$$T_n = \frac{T_{Amax}}{T_{end}} \tag{3.17}$$

where T_{Amax} is the time when amplitude reaches the maximum value in a shake and T_{end} is the actual shake duration measured by wireless sensors. To find the corresponding shaking intensity that has caused maximum amplitude, T_n must be multiplied by pattern shake duration which is 1.5 and 3 seconds for small and medium/large trees, respectively.

3.4 Results

3.4.1 Shake Duration

The actual shake duration was measured during the harvest, sensed and recorded by the precise wireless accelerometer sensors. Figure 3.7 shows the shake duration for small trees was about one second (66%) longer than the set time for the shake pattern on the machine. Shake's durations of medium and large-size trees are shown in Figure 3.7. On medium-size trees, shakes 1, 2, and 4 (patterns 1 and 3) were 44%, 58%, and 41% longer than a 3-second intended shake. On large trees, shake 4 (pattern 3) was 39% longer than a 3-second intended shake duration.

Shake 3 on medium and large trees was the closest to the designed shake duration. This shake has used a constant shake intensity (Pattern 2).

The shake duration of all other shakes, which were using a non-constant shake intensity, was significantly longer than the designed duration. The extended shake time increases the chance of tree damage. Thus, finding the optimum shake intensity for each individual tree can mitigate the need to change intensity during a shake and reduces excessive extended shake duration. Table 3.2 shows all individually measured shake duration for every experiment. The last two rows show the average and standard shake duration for each shake.

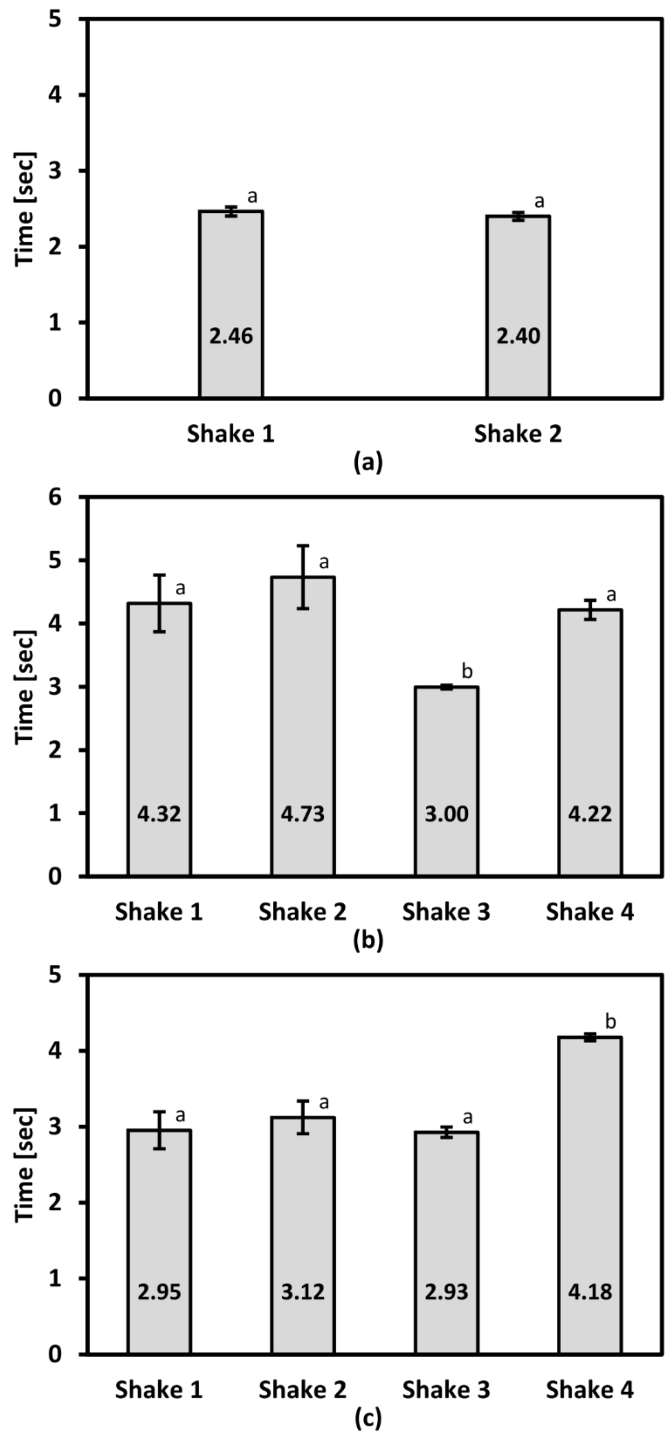


Figure 3.7 Shake duration of (a) small, (b)medium and (c) large trees measured using accelerometer sensors. Error bars showing standard error. Same letters on each bar in the same figure is not significantly different (p>0.05).

Table 3.2 Shake duration of the small, medium, and large trees in seconds (unrecorded data points are shown as blank). The last two rows show the average and standard error of each column.

Experiment	Small		Medium				Large			
	Shake 1 [sec]	Shake 2 [sec]	Shake 1 [sec]	Shake 2 [sec]	Shake 3 [sec]	Shake 4 [sec]	Shake 1 [sec]	Shake 2 [sec]	Shake 3 [sec]	Shake 4 [sec]
1	2.36	2.40	6.29	5.45	3.05	4.22			2.94	4.11
2	2.58		6.47	7.50	3.02	5.19	2.98	2.91	2.91	4.14
3	2.78	2.51	4.18		3.04	4.96	3.39	3.33	2.83	4.19
4	2.39	2.51	2.23	3.02	2.84	4.08	2.87	3.24	3.03	4.10
5	2.33	2.50	4.10	4.53	3.00	3.67	1.86	1.90	2.85	4.01
6	2.24	2.06	4.60	5.01	2.97	3.39	2.97	3.04	2.85	4.56
7	2.77		5.16	5.06	3.20	4.20	4.05	4.27	2.99	4.13
8	2.47	2.41	2.70	2.76	2.91	4.13	3.63	3.64	2.60	4.16
9	2.29	2.38	4.46	5.76	2.88	4.24	1.85	2.74	2.82	4.15
10	2.41	2.42	3.00	3.49	3.00	4.10	2.96	3.02	3.45	4.23
Average	2.46	2.40	4.32	4.73	2.99	4.22	2.95	3.12	2.93	4.18
Std. Error	0.06	0.05	0.45	0.50	0.03	0.17	0.24	0.22	0.07	0.05

3.4.2 RMS of Vibration

Using the wireless sensor system, the vibration of each tree was recorded. One sensor (sensor 1) was attached to the shaker machine, and three sensors (sensors 2 to 4) were attached to each tree along one branch path (see Figure 3.6). This can show how vibration acceleration has been transmitted through the tree's branches. Figure 3.8 shows how the root mean square (RMS) of vibration acceleration is transmitted through the tree canopy for each shake pattern. Although patterns used to shake medium and large trees were the same, these two sizes responded quite differently to these patterns. In medium-size trees (Figure 3.8B), for the first two shakes (using pattern 1), acceleration increased from the shaker (sensor 1) to the first and secondary branches of the tree (sensors 2 and 3), but it decreased by the tertiary branches (sensor 4). In large trees (Figure 3.8C), acceleration decreased from shaker (sensor 1) to tree (sensor 2) then increased to get to the end of the branch. This shows trees with different trunk sizes will transmit vibration differently.

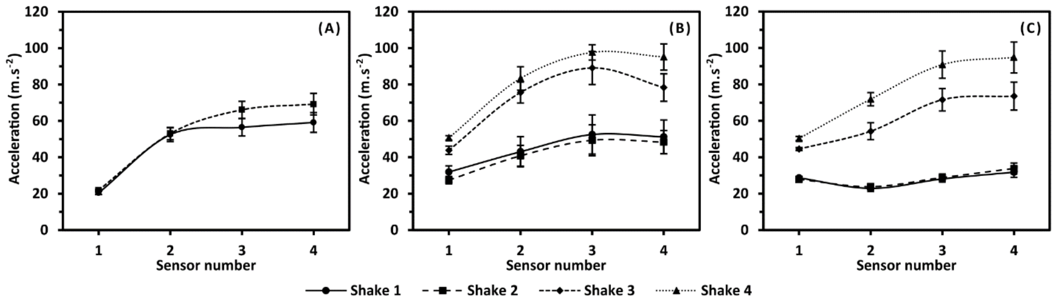


Figure 3.8 RMS of vibration in small size trees (a), medium size trees (b) and large size trees (c). Sensor 1 was attached on shaker machine, sensor 2 was attached to a main branch, sensor 3 was attached to small branch and sensor 4 was attached near fruits.

3.4.3 Suggested Shaking Intensity

Wavelet analysis was performed for each shake on every individual tree. Figure 3.9 shows the Continuous wavelet transform (CWT) magnitude scalogram when shaking a tree using the four shake patterns. Bright color represents the frequency with the highest amplitude at each time step. This figure confirms that the shaker machine was able to apply all the designed patterns to the trees.

The changes of the vibration frequency and amplitude vs. time were extracted from CWT analysis. An example is shown in Figure 3.10, which is extracted data of Figure 3.9(a). The time that the tree has experienced maximum shaking amplitude is named T_{Amax}. Shaking frequency at this time was recorded for all the trees. This shaking frequency is plotted vs. tree trunk circumference in Figure 3.11.

Figure 3.11 also shows the intensity at which each tree has experienced the maximum amplitude of shake measured by sensor 4, regardless of shaking pattern. Each dot in this figure represents a tree. A power law trend line with the equation of $y = 5.9073x^{0.5082}$ was the best fit ($R^2 = 0.79$) and was added to this figure. This equation enables a shaker operator to find proper shaking intensity for each tree by knowing the size of the tree circumference. Thus, an average-sized small, medium and large tree (circumference sizes of 37.4, 86.6, and 113.7 CM) will have optimal shaking intensity of %37, %57, and %65, respectively. Similarly, the best shaking intensity (nominal intensity) can be extracted using Figure 3.11.

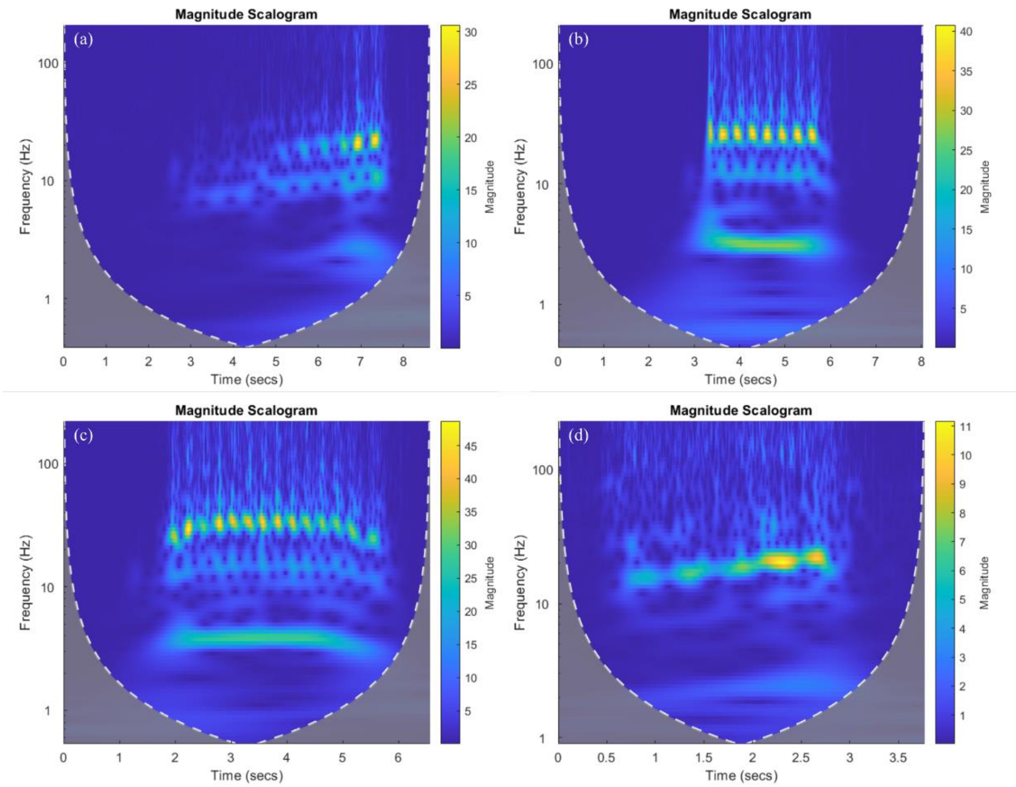


Figure 3.9 Continuous wavelet transform (CWT) magnitude scalogram shows frequency and magnitude components of vibration vs time when shaking a tree using (a) pattern 1 (b) pattern 2, (c) pattern 3 and (d)pattern 4.

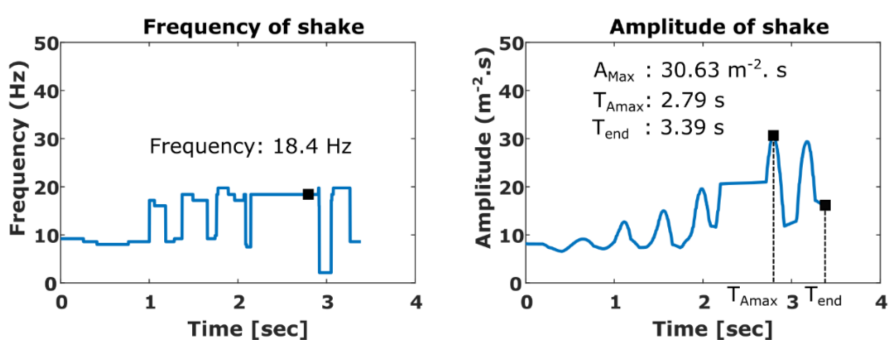


Figure 3.10 Frequency and amplitude of shake vs time extracted using previous figure data.

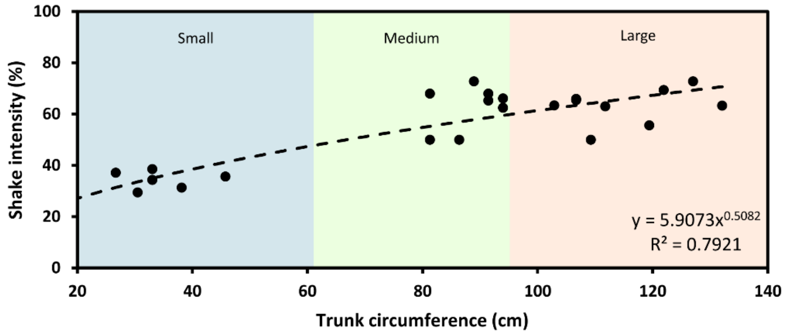


Figure 3.11 Best shaking intensity vs. tree circumference

3.5 Conclusion

The effectiveness of a pattern for better energy transmission dependent on tree canopy specifics, including trunk diameter (equivalent to trunk circumference), trunk height, and tree canopy size (Horvath & Sitkei, 2005). Therefore, in this study, trees were divided into three groups based on their trunk size: small, medium, and large.

It was observed that in most cases, the actual shake duration generated by the machine was significantly longer than the shake pattern. For small trees, the actual shake duration was 66% and 60% longer for the first and second shake. For medium trees, it was 44%, 58%, and 41% longer for the first, second and fourth shake. On large trees, it was 39% longer for the fourth shake.

The effect of each pattern on each trunk size was studied using wireless sensors. Although shake patterns used to harvest medium and large trees were the same, these two groups showed different vibration distribution through the canopy. This indicates trunk size should be considered as a valuable parameter to choose a shaking intensity.

A model was developed to find the optimal shaking intensity for any given trunk size for pistachio trees. The optimal shaking intensity can be calculated using this model. A similar model can be generated using a similar method in this study for any tree variety. Further study is needed for improvement and integrating this model with the shaker computer to eliminate the operator to manually program the shake pattern for each tree.

The optimized parameters, sensors, and control system developed in this study can be used to develop the next generation of smart harvesting machines, machines that can calculate optimal shake intensity based on the tree trunk size.

3.6 Acknowledgment

The work in this chapter was partially funded by California Pistachio Research Board and California Olive Committee. The authors are grateful to Dr. Ruijun Ma for this help in data collection helpful suggestions. The authors would like to acknowledge Wonderful Company LLC for allowing us to access their orchards and helping us during in-field data collection.

Chapter 4

A New Fruit Removal Head for an Olive Harvesting System

4.1 Introduction

Production acreage of table olives, California's signature crop, has significantly decreased in recent years due to the high cost of production and a small margin of profit. Harvesting is a major cost of production for table olives. Currently, the majority of table olives are hand-harvested. Although some growers are using trunk shakers with some success, this method has not been widely utilized because older trees often have large or irregular-shaped trunks that cannot be harvested by trunk shakers. While trunk shakers work on smaller trees, growers are hesitant to remove and replace high yield producing older trees with younger trees. Mechanical harvesting, using contact canopy shakers, is a promising method for harvesting table olives. Scientists at UC Davis have developed a prototype of a canopy shaker that has been tested and has shown some level of success. The UC Davis-designed canopy shaker is very similar to the canopy shaker used in harvesting process oranges in Florida (Castro-Garcia et al., 2019; S. K. J. U. Savary, Ehsani, Salyani, Hebel, & Bora, 2011). The proposed technique showed promising results, but it was relatively heavy and could not accommodate the shape of the tree very easily. Despite all past efforts, there is still a need for a cost-effective and efficient harvesting system to match the needs of existing table olive trees.

4.2 Objectives

The ultimate goal of this project is to develop a low-cost harvesting head for the table olive industry in California. The specific objectives were as follows:

- Reduce the harvesting cost for table olives.
- Develop a cost-effective fruit removal system for existing conventional olive orchards.
- Ensure the harvesting system is highly efficient and does not damage the trees or the fruit.

4.3 Experimental Procedures

Trees in two olive orchards were visited and evaluated. Canopy size height and width were measured (Figure 4.1) to design a properly sized harvesting system. Also, current mechanical harvesting machines were studied to find their strength and weaknesses.

Figure 4.1 Evaluating trees, looking at small and large branches within the canopy

Trunk shakers are one of the mechanical harvesting systems currently used for table olives. This type of harvester needs about 0.6 to 1 meter of clearance on the trunk to attach and subsequently shake a tree. This can be challenging, especially in conventional olive orchards where trees have not been trained for mechanical harvesting. Trees might have short trunks or an irregular tree shape, which would inhibit a shaker from attaching to these trees, as shown in Figure 4.2.

Trunk shakers vibrate the tree trunk, and the vibration energy travels from the trunk to the large branches and small branches (Figure 4.2), causing olive fruit to detach. Because of their wood properties, olive trees tend to significantly damp the vibrational energy. Also, the olive has a large detachment force to fruit weight ratio that separates it from most other fruits usually harvested by trunk shakers. This ratio can get to 200-400 with oil varieties and 100-200 with table olive varieties (Ravetti & Ravetti, 2008). Due to the damping of energy, trunk shakers must shake trees at high intensity to get a high fruit removal percentage. This can be harmful to the tree's trunk and root system. On the other hand, there are canopy shakers which, instead of vibrating tree trunk they vibrate the tree's canopy. This is a much safer approach for the health of trees over time but there is no commercially available canopy shaker that is specifically designed to harvest olives.

Figure 4.2 Not enough trunk length for trunk shaker to attach (left); Irregular trunk shape inhibiting use of trunk shaker (right)

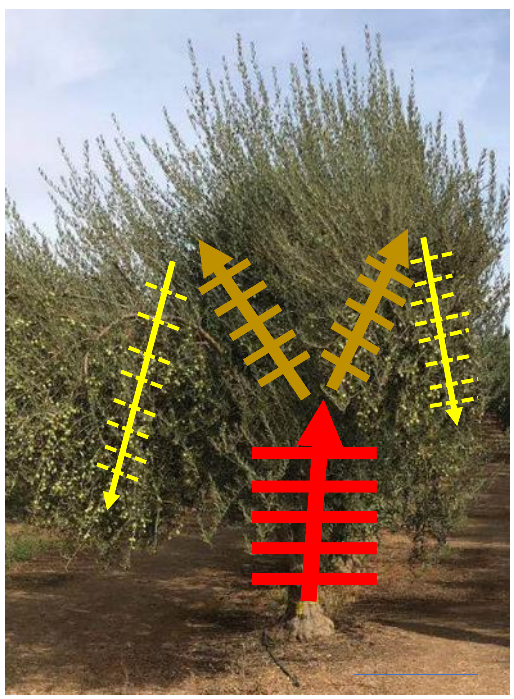


Figure 4.3 Vibration dampening as the vibration travels from thick trunk to large branches and small branches, causing olive fruit to detach.

4.4 Design Procedures

A canopy shaker specifically for table olive trees was designed. This design has three major advantages over current solutions.

1. It can compress and squeeze tree canopy.
2. It is adjustable to a range of tree sizes and heights.
3. It can be used to harvest fruit within the row.

Squeezing canopy while shaking it can improve harvest efficiency. This can reduce the amount of energy needed to harvest each tree, resulting in a safer harvest process. Figure 4.4 shows a harvesting mechanism with three wings that can squeeze the canopy. It has four active harvester wheels that vibrate in a linear motion.

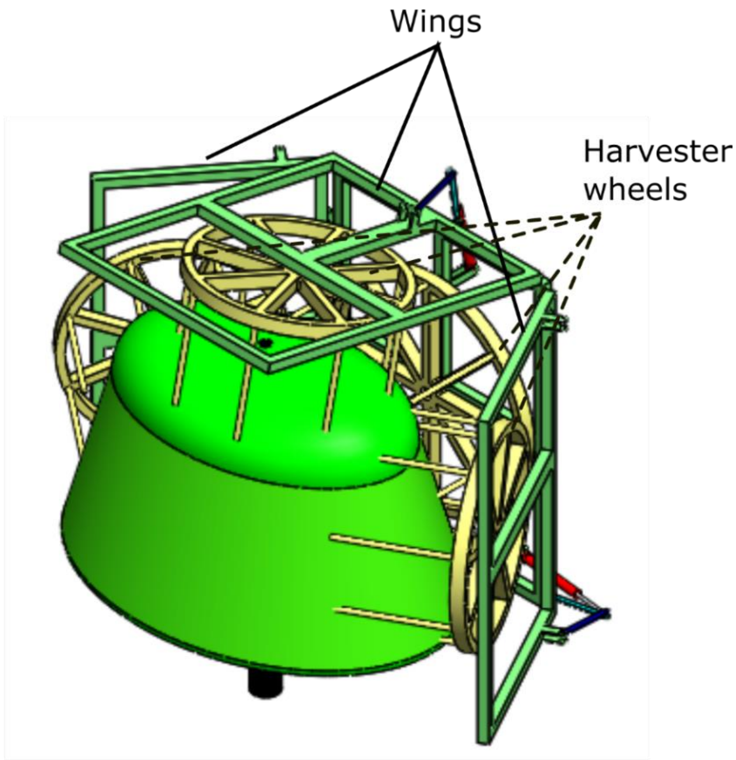


Figure 4.4 Proposed harvesting mechanism with tree wings and four harvester wheels (yellow).

It was decided to build a simpler version with two wings and two harvesting wheels, as shown in Figure 4.5 for the first trial. This design uses one linear hydraulic cylinder to open and close each wing (two in total). A slider-crank mechanism has been utilized to move harvesting wheels back and forth to generate a shaking pattern.

Table 4.1 shows the amplitude that can be produced using this crank-slider mechanism. This mechanism uses one hydraulic motor on each wing. The crank is directly connected to the hydraulic motor and the harvesting wheel is mounted on a slider, see Figure 4.6.

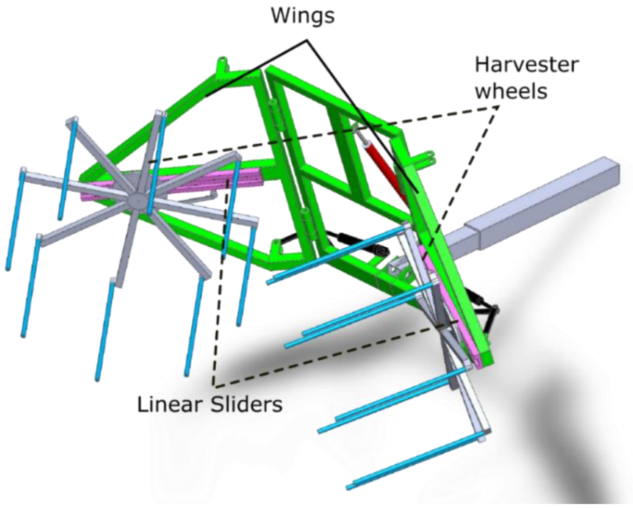


Figure 4.5 Design of first version of canopy shaker.

Table 4.1 Range of amplitude that can be generated using the various crank radius

Crank Radius (cm)	Amplitude (cm)
5	10
7.5	15
10	20

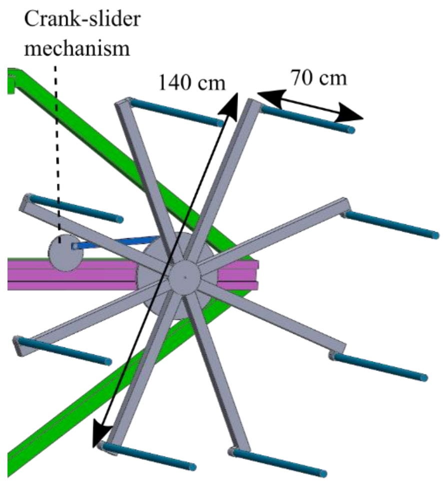


Figure 4.6 Crank-Slider mechanism is used to move the harvesting wheel back and forth to shake olive trees

The harvesting head was attached to a Bobcat 337 equipped with a retractable boom. Using this platform harvesting head was able to rise up to a height of 4.5 *m* to harvest trees up to 6 *m* see Figure 4.7.

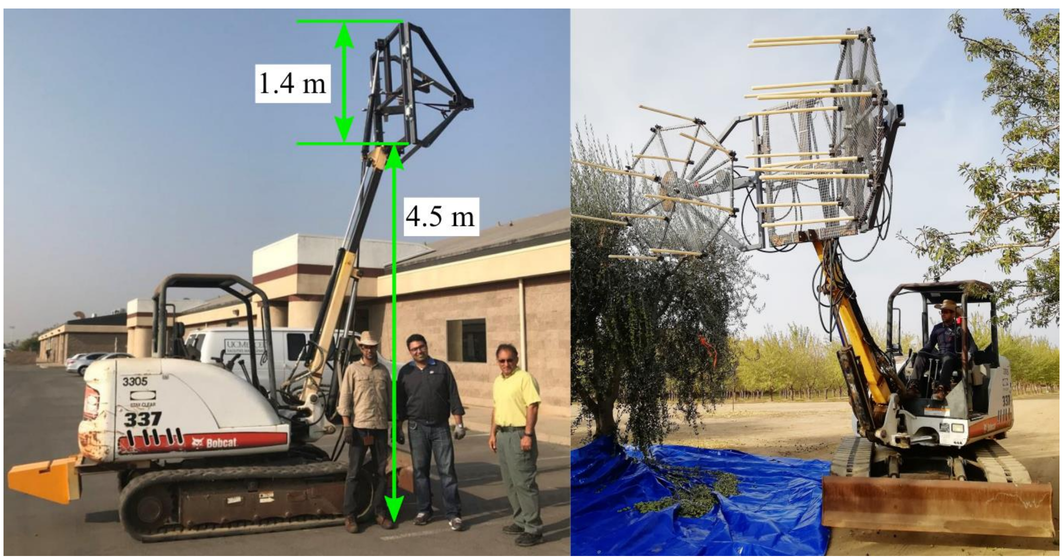


Figure 4.7 Head frame attached to the Bobcat 337. Harvest head could rise to 4.5(m) from the ground and harvest trees up to 6 (m).

This design has been tested in an olive orchard, and the shaking system did not generate enough acceleration for an efficient olive harvest. The design was modified to achieve higher acceleration and better fruit removal by changing the shaking mechanism. The same harvesting wheel was attached to an off-center shaft connection and driven by the same hydraulic motor using a chain sprocket system. A number of shaking rods were needed to increase to improve contact area with the tree canopy enhancing transmission of vibration energy to tree canopy, see Figure 4.8. Figure 4.9 shows the shaking wheel with four extra rods attached.

To measure and record vibration, the same wireless sensor system from the previous chapter was used. Each sensing module has a built-in 3D accelerometer, wireless module, and a battery. The data logger unit connects wirelessly to all sensing modules and records their data on a flashcard, see Figure 2.3.

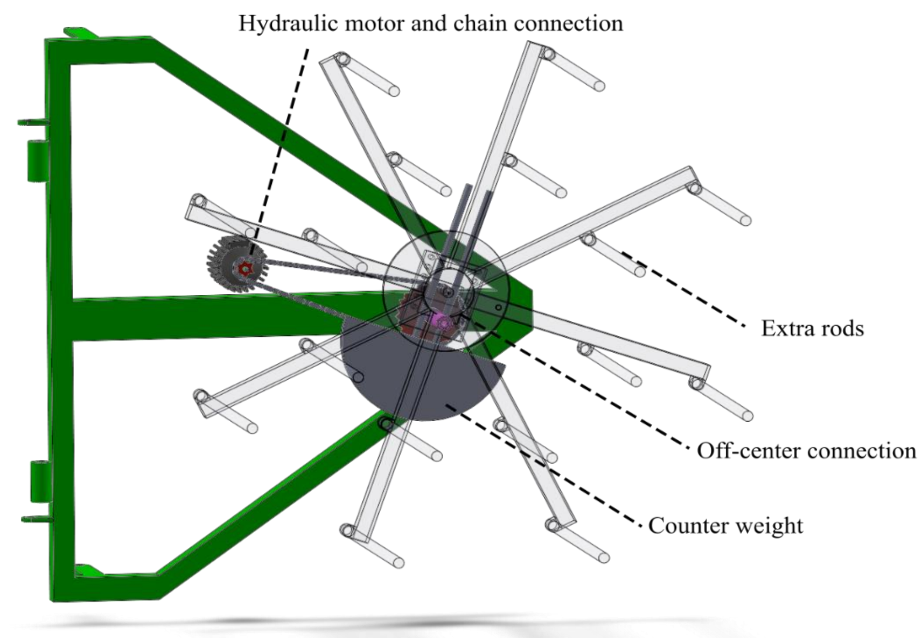


Figure 4.8 Modified design using an off-center connection allowing the harvesting wheel to generate circular shaking motion.

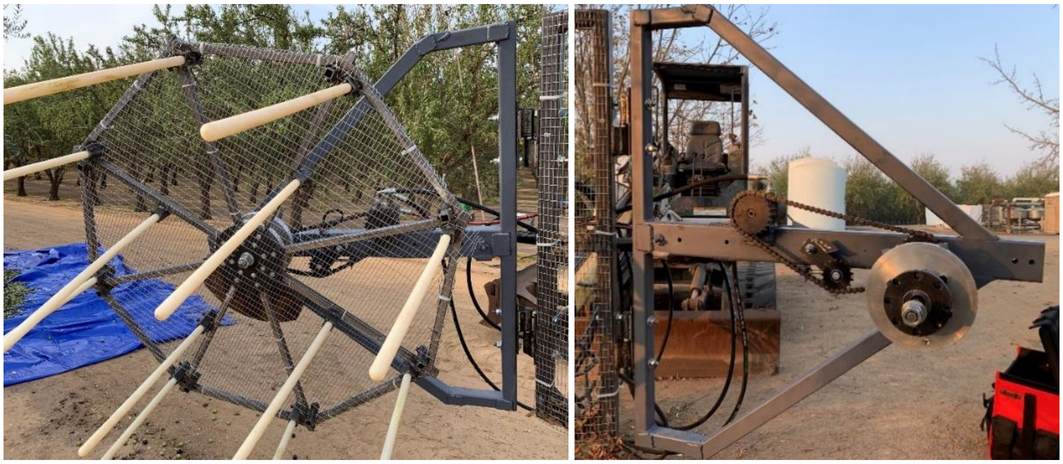


Figure 4.9 Modified design without shaking wheel attached (right) and with shaking wheel and rods attached (left)

4.5 Results

These two harvesting machines were tested in an Olive orchard on Oct 1st and Nov 11th, 2018, respectively. Three wireless accelerometer sensors were attached to each tree, one attached to the tree trunk, one to the main branch and one to the secondary smaller branch to measure how vibration energy travels through a tree.

Using this sensor system, the two canopy shaker harvesters have been compared with a commercial trunk shaker harvester which was available at the experimental site. Figure 4.10 shows the acceleration of each sensor of these three harvesting machines.

Collected data from both canopy shakers (Figure 4.10 A and B) showed that the small-diameter branches vibrate at a higher amplitude than the larger primary branches and trunk. This shows that a much smaller amount of energy goes through the tree trunk and root system, which could result in less damage to the tree compared to the trunk shaker. Figure 4.10 (C) shows similar data for the trunk shaker, it shows the measured vibration amplitude in the trunk was much higher compared to small branches. This means the newly developed harvester machine applies most of the energy where the fruits are located and therefore is more efficient.

Table 2 shows shaking frequency and maximum acceleration at small branches produced by our canopy shakers and the trunk shaker.

Table 4.2 Working frequency and maximum amplitude at small branches of these three harvesters.

	Canopy Shaker	Modified Canopy Shaker	Trunk Shaker
Frequency	3.7 Hz	3.5 Hz	15.5 Hz
Max Amplitude	100 ms^{-2}	221.5 ms^{-2}	125.5 ms^{-2}

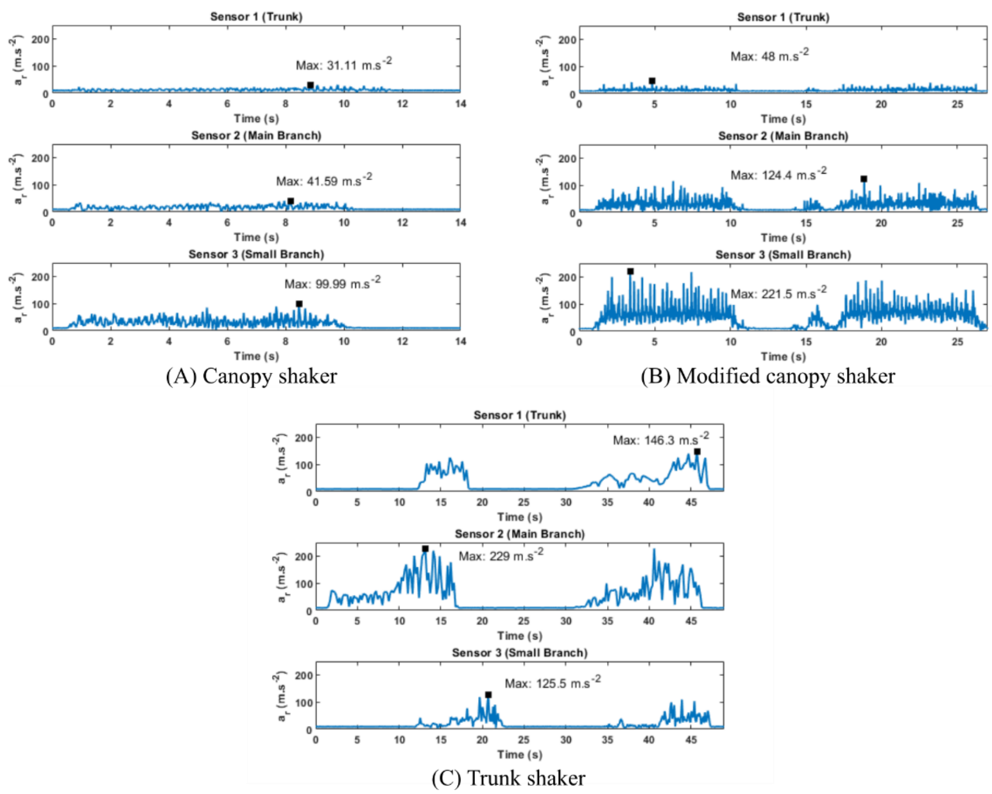
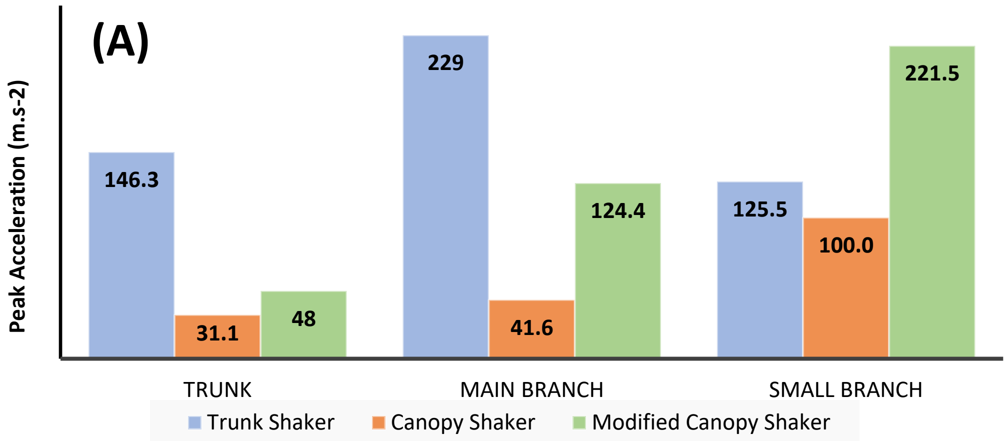


Figure 4.10 Vibration amplitude measured from an Olive tree using (A) first version of Canopy shaker, (B) modified canopy shaker and (C) a commercial Trunk shaker

Figure 4.11 shows the modified canopy shaker was able to deliver the highest peak and RMS acceleration at small branches compared to the first version of the canopy shaker and the trunk shaker.

The first harvesting machine was not quite successful in removing fruit due to lower shaking frequency and lower shaking amplitude, but the modified canopy shaker was able to harvest as efficiently as the trunk shaker while transferring much lower vibration energy to the tree trunk compared to the trunk shaker.



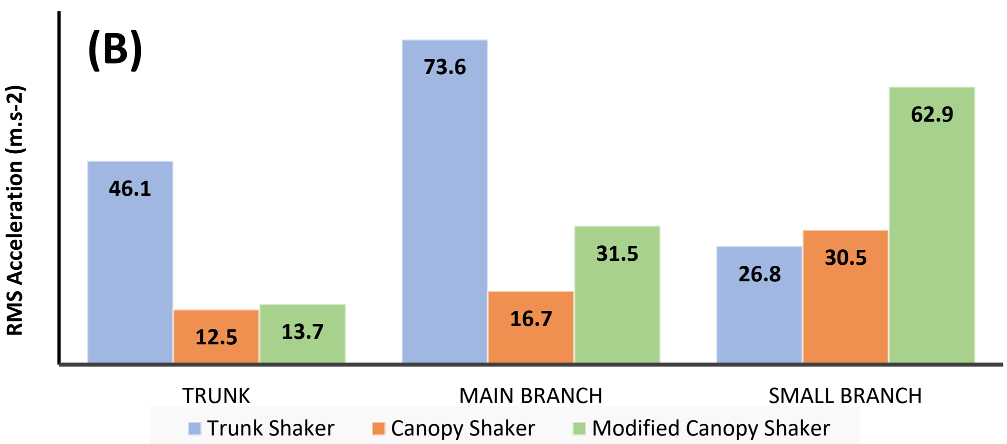


Figure 4.11 (A) Maximum peak acceleration produced by these three harvesters at each part of a tree, (B) Root Mean Square (RMS) of vibration measured at each part of a tree).

4.6 Conclusion

A new canopy shaker head was designed and manufactured to harvest olive fruit. Acceleration in the tree was measured by an in-house developed wireless sensor system. The modified shaker head improved maximum generated peak acceleration in small branches of the olive tree by %76.5 and improved RMS of vibration by %134.7 while decreasing vibration in the trunk by %70. The harvesting efficiency was evaluated visually, the modified shaker was able to harvest olives as efficiently as a commercial trunk shaker machine.

Chapter 5

Combining Trunk and Canopy Shaking for Olive Harvester

5.1 Problems and Significance

Harvesting is a major cost of production for many crops, including olive. Although some olive growers are using trunk shakers with some success, this method has not been widely utilized because the willowy characteristics of olive trees prevent the effective transmission of vibrational energy from the trunk to the small branches where the fruits are located. To remove the fruit, a trunk shaker requires a large amount of energy which can cause damage to the tree. Also, for some older orchards, the trunk shaker may not be an option due to the size and shape of the canopy.

Engineers at UC Davis developed a prototype of a canopy contact shaker that has been tested and has shown some level of success, which is very similar to the canopy shaker used in the harvesting of process oranges in Florida. Ehsani's group at UC Merced used an alternative design approach and developed a lighter weight (about 50% lighter) canopy contact shaker-based fruit removal system that can accommodate larger trees. This system has shown some promising results as well. The UC Merced design was able to produce the maximum shaking energy at the fruit level as opposed to the trunk, and hence, less damage to the tree. However, it took a longer time to shake each tree.

Based on some initial field testing conducted in the fall of 2019, it seems that a combination of trunk shaking and canopy shaking can provide the best fruit removal for olives. In this project, we propose to evaluate the effect of a combination of trunk and canopy shaking on olive fruit removal. We intend to conduct extensive field tests to assess the best design parameters, such as amplitude and frequencies. These parameters are needed for designing and building a system that combines both canopy and trunk shaking together.

5.2 Previous Works

Mechanical harvesting of olives was initiated in the US in the 1940s. The main goal was to develop a cost-effective technique to harvest olive fruit for both table and oil extraction purposes (Sola-Guirado et al., 2014). Among all proposed methods, mechanical shaking has been the most successful approach for fruit removal. Different types of shakers such as a trunk shaker, branch shaker, and canopy contact shaker were developed (Famiani et al., 2014; Francisco Jimenez-Jimenez et al., 2015). To increase the efficiency of using these shakers, previous research studies suggested using high-density hedgerow orchards with limited tree height. Trunk shakers had lower fruit removal efficiency due to the damping effect of branches (Castro-Garcia et al., 2015; Louise Ferguson & Garcia, 2014). Besides the lower efficiency, damage to the bark of the trunk and branches causes lower yield in future years and increases the risk of infestation and disease in the trees(Francisco Jimenez-Jimenez et al., 2015). For other types of shakers, especially canopy shakers, damage to the branches and final fruit quality issues such as cuts and flesh injury should be taken into consideration (L Ferguson et al., 2010). All these types of damage reduce the market acceptability, especially of green processed table olives. To solve the issues with mechanical harvesting of traditional orchards, (L Ferguson et al., 2010) suggested considering modifications in both the canopy size of conventional trees and mechanical harvesters simultaneously.

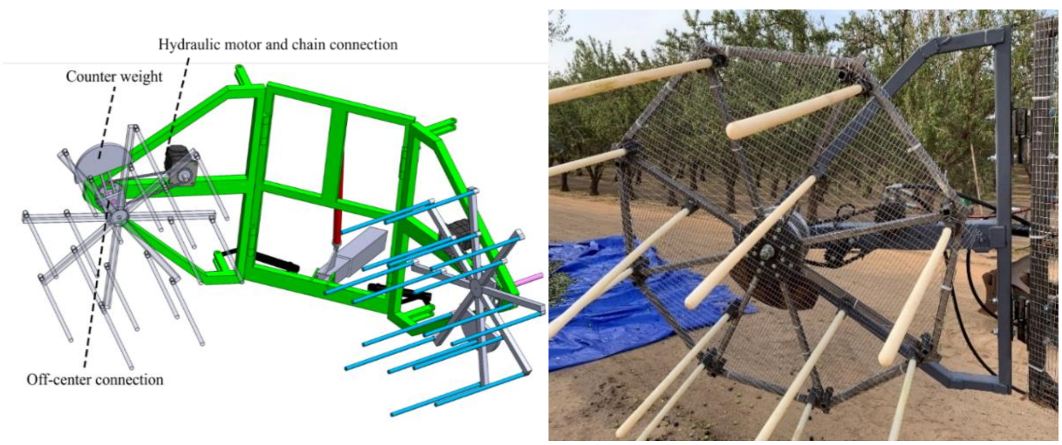


Figure 5.1 UC Merced fruit removal canopy shaking head

This project is the continuation of a previously funded project by the California Olive Committee (COC) to UC Merced. Figure 5.1 shows the UC Merced canopy shaker fruit removal system.

The UC Merced-designed canopy shaker was tested in an olive orchard in 2018 and 2019 during harvesting season. To measure and record vibration and force distribution throughout the canopy, we have developed and built a wireless sensor system consisting of a data logger unit and multiple sensing modules. Each sensing module has a built-in 3D accelerometer, wireless module, storage module and a battery. The data logger unit connects wirelessly to all sensing modules and triggers data collection procedure (Figure 5.2).

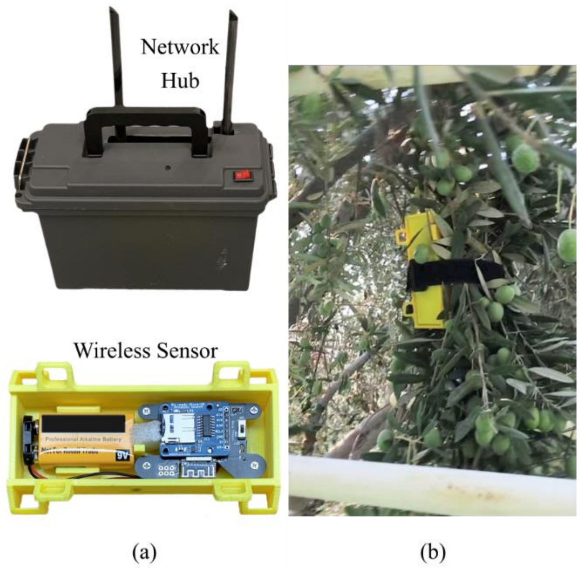


Figure 5.2 Wireless sensor module and network hub (a) and a wireless sensor module installed on olive branches for data collection (b).

5.3 Objectives

The ultimate goal of this study is to develop a highly efficient, low-cost fruit harvesting machine for olives by the 2021 harvest season. The specific objectives are as follows:

- Study whether a combination of canopy shaker and trunk shaker is a superior method to other alternatives in maximizing fruit removal and minimizing harvest time.
- Find the best shaking parameters (frequency, amplitude, duration) for a combination of trunk shaker and canopy shaker.
- Evaluate the effects of fruit removal using both shaking systems on fruit and tree damage.
- Based on the results from field tests, design a new harvesting system for an olive that uses widely available trunk shaking equipment modified with a relatively low-cost canopy-contact harvester and catch-frame system.

5.4 Experimental Procedures

An experiment was done in Nickels olive orchard (Woodland, CA) on September 30th, 2020. A trunk shaker built by Orchard Machinery Corporation (OMC) was selected and has been tested alongside the UC Merced canopy shaker. For each shaker machine (trunk and canopy shaker), three different shaking frequency was chosen. Eleven trials were conducted, including the nine combinations of shaking frequencies (Figure 5.3), one trial on using solely trunk shaker and one trial using UC Merced canopy shaker only (Table 5.1). Each trial was done in three replicates (total of 33 trees). Canopy shaker has been set to 2″ off-center distance, generating oscillation with 4″ amplitude. Rotational speed was set to 100, 150 and 200 rpm for the experiment. The trunk shaker intensity was set to low, medium, and high. Shake duration was set to 15 seconds. There were three wireless accelerometer sensors installed on each tree canopy. Two sensors were attached on the side of canopy shaker, and one was installed on the opposite side.

Table 5.1 Experiment design for selecting the optimum combined shaking frequency. Each treatment will be replicated three times.

Trunk shaker intensity / Canopy shaker (rpm)	Low	Medium	High
100	Trial-1	Trial-2	Trial-3
150	Trial-4	Trial-5	Trial-6
200	Trial-7	Trial-8	Trial-9

Canopy shaker	Trial-10
Trunk shaker	Trial-11

Before each shake, 4 to 6 tarps were laid on the ground to collect harvested olives. After the shake, mechanically harvested olives were weighed, and a sample was labeled and prepared to be sent to a laboratory for quality rating. A gleaning crew was hired to remove the remaining olives on the trees. The manually harvested fruit was weighed and recorded. Harvest efficiency is calculated using equation (5.1).

Figure 5.3 Trunk shaker and canopy shaker, shaking an olive tree simultaneously

$$Efficiency = \frac{Mechanically\ harvested\ (lb)}{Manually\ harvested\ (lb) +\ Mechanically\ harvested\ (lb)} \times 100 \qquad (5.1)$$

5.5 Results

Harvest efficiency for each of 11 trials has shown in Figure 5.4. Trial 1 through trial 9 has used both UC Merced canopy shaker and the OMC trunk shaker. Trial 10 has used only the UCM canopy shaker and trial 11 has used the OMC trunk shaker solely.

This figure shows almost all the trials using both shakers simultaneously, except trial 8 has had better harvest efficiency than using each type of shaker individually. Figure 5.5 shows the average harvest efficiency of all three shaking methods. This figure shows combined shaker method has improved harvest efficiency by 41% and 19% compared to canopy shaker and trunk shaker, respectively.

Figure 5.6 shows the root mean square (RMS) of recorded vibration using the accelerometer sensors on the olive tree canopies. It shows that the vibration recorded in the canopy has been much more uniform and higher in the combined method compared to the other two methods. This supports the high harvest efficiency data using the combined method.

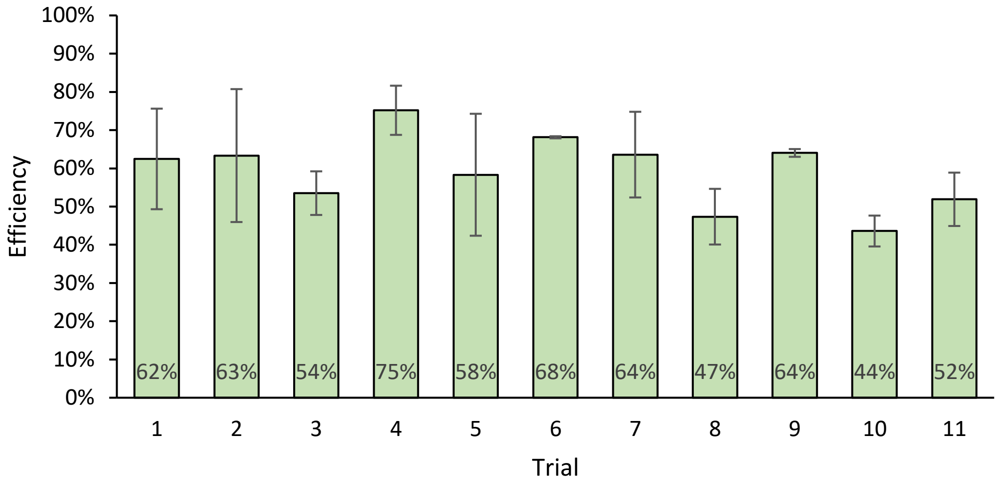


Figure 5.4 Harvest efficiency for all trials. Trials 1 to 9 were used both canopy shaker and trunk shaker simultaneously, Trial 10 has used UC Merced canopy shaker only and trial 11 has used the OMC trunk shaker.

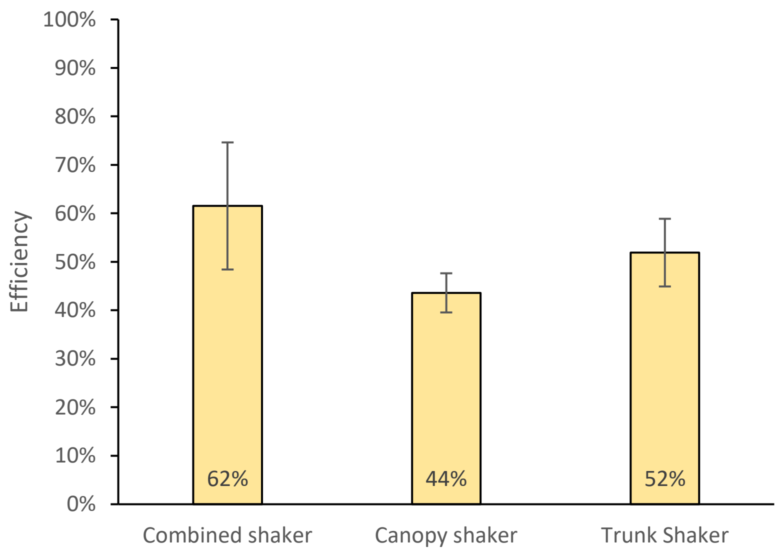


Figure 5.5 Comparing harvest efficiency of all three methods.

These results strongly show shaking an olive tree simultaneously using a trunk shaker and a canopy shaker will result in higher harvest efficiency. Among the nine trials which used both shakers, trials 4 and 6 showed the best harvest efficiency of 75% and 68%, respectively.

The price per ton for each trial is shown in Figure 5.7. It shows that trials five and six were able to harvest higher-quality olives among all other trials, including using these shakers alone.

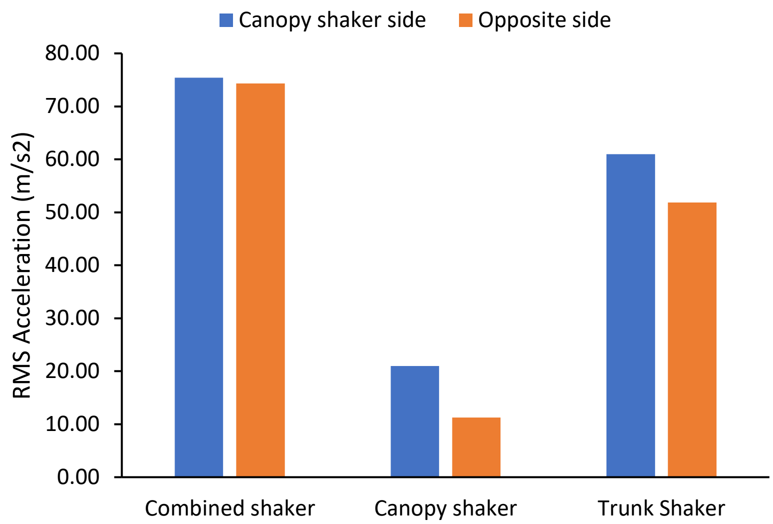


Figure 5.6 Root Mean Square of acceleration recorded by wireless accelerometer sensors installed on olive trees canopy.

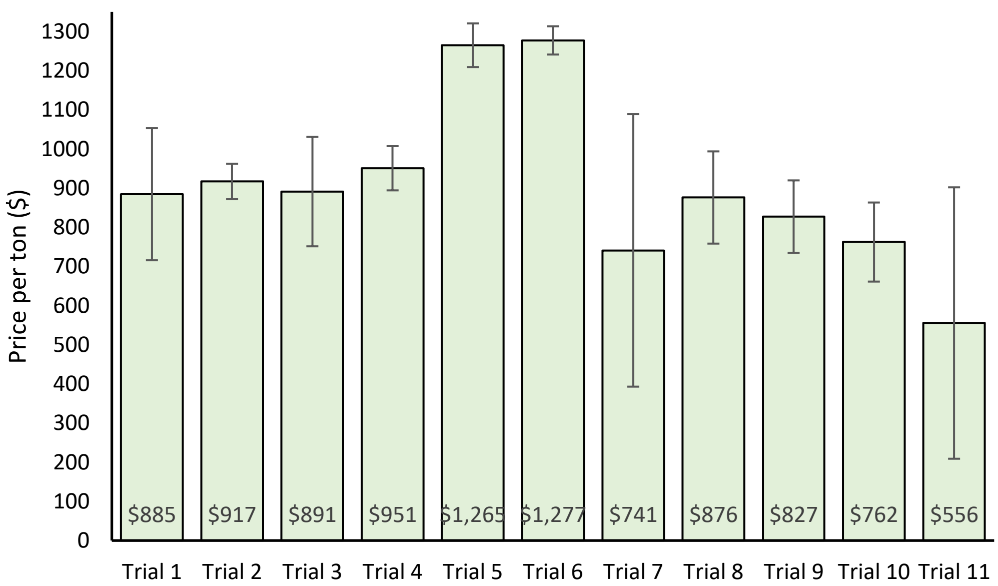


Figure 5.7 Price per ton for each trial.

Figure 5.8 compares price per ton of the three shaking methods. This figure confirms using combined shaker is the most profitable method for olive harvesting comparing to using canopy or trunk shaker individually.

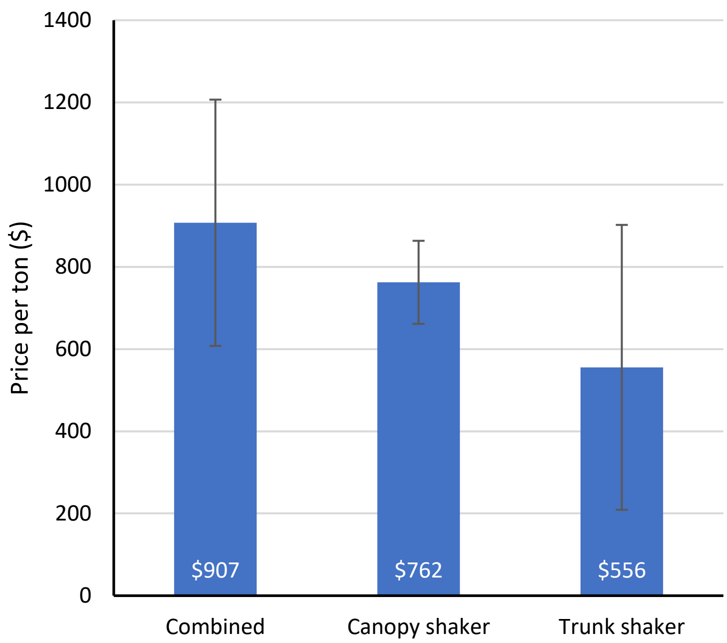


Figure 5.8 Comparing harvested olive quality between three shaking methods.

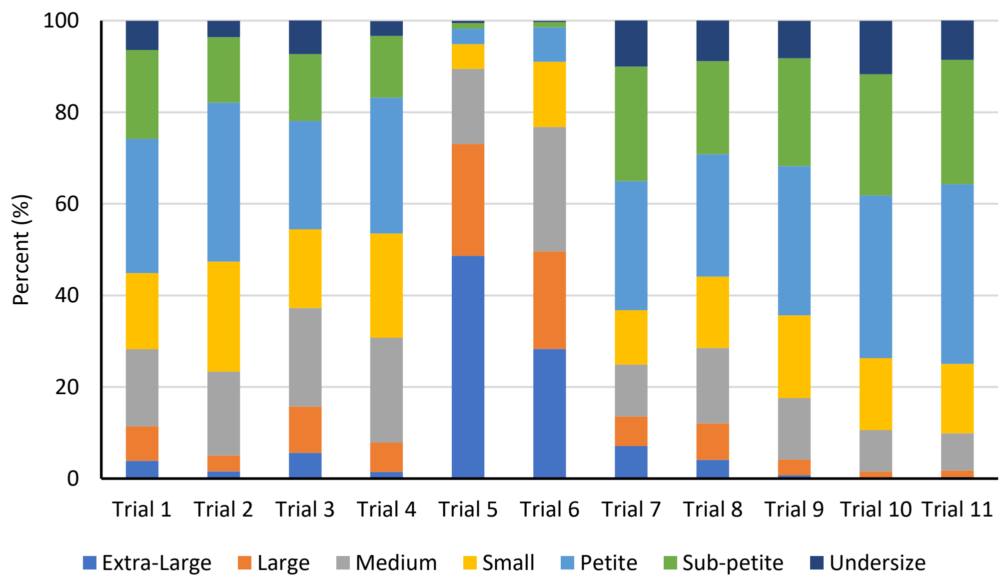


Figure 5.9 Fruit size harvested in each trial.

Figure 5.9 shows harvested fruit size in each trial. It shows that trials five and six could harvest the highest amount of extra-large and large fruits compared to all other trials.

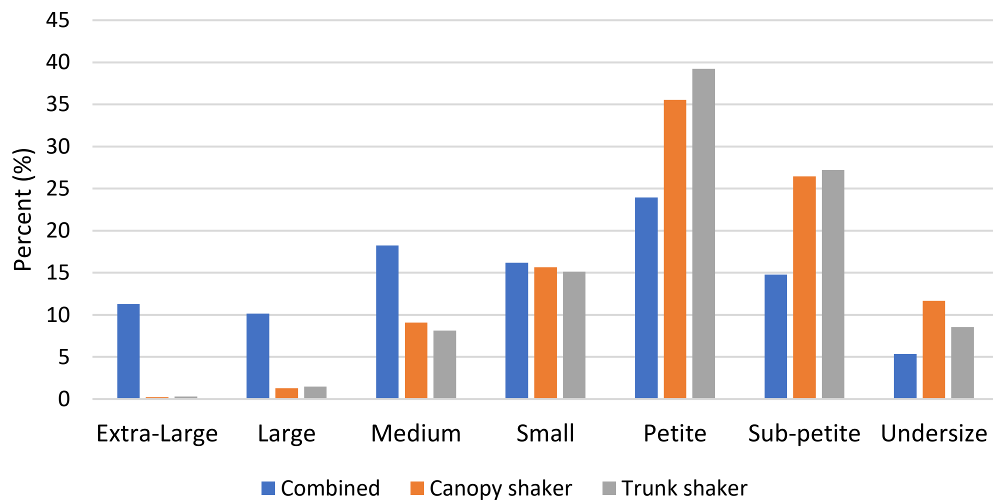


Figure 5.10 Harvested fruit size using combined canopy and trunk shaker.

Figure 5.10 shows the percent of fruit size in samples sent to the quality control lab. The combined shaker method was able to harvest significantly more extra-large, large, and medium olives compared to the other two methods.

5.6 Conclusion

In this project effect of using a trunk shaker and a canopy shaker on olive trees was studied. An extensive field trial was done on September 30th, 2020, in nickels olive orchard (Woodland, CA). The used canopy shaker was designed and built by Dr. Ehsani's research group at the University of California Merced, and the trunk shaker was built by Orchard Machinery Corporation (OMC). Eleven test trials were designed and performed, including nine trials using both shakers and one trial to use each shaker individually. Harvest efficiency was measured by measuring mechanically harvested fruits and manually harvested fruits. The combined shaking method achieved harvest efficiency up to 75% (trial 4), which is significantly higher than the harvest efficiency of trunk shaker and canopy shaker alone at 52% and 44%.

The quality of harvested fruits was evaluated by price per ton. Combined shaker was able to achieve price per ton of $1250+ (trials 5 and 6) while trunk shaker and canopy shaker were able to achieve price per ton of $556 and $762. On the other hand, the combined shaker was able to harvest the highest amount of extra-large, large, and medium-size olives, resulting in a higher price per ton.

All in all, this project strongly suggests that a combination of trunk shaker and canopy shaker is much more effective for harvesting olive fruit in terms of harvest efficiency, price per ton, and harvested fruit size.

Chapter 6

An Olive Canopy Shaker for Mature Olive Trees

6.1 Problems and Significance

Harvesting is the major cost of production for many crops, including olive. Mechanical harvesting of olives was initiated in the US in the 1940s. The main goal was to develop a cost-effective technique to harvest olive fruit for both table and oil extraction (Sola-Guirado et al., 2014). Among all the proposed methods, mechanical shaking has been the most successful approach for fruit removal and machines were commercially available. Different types of trunk, branch and canopy contact shakers were developed (Famiani et al., 2014; F Jimenez-Jimenez et al., 2015). The efficiency of these shakers was improved with canopy management that limited tree height and formed upright scaffolds. Trunk shakers had lower fruit removal efficiency due to the damping effect of branches (Castro-Garcia et al., 2015; Louise Ferguson & Garcia, 2014). Besides the lower efficiency, damage to the bark of the trunk and branches causes lowered yield in succeeding years and increases the risk of infestation and disease in the trunks (F Jimenez-Jimenez et al., 2015). For other types of shakers, especially canopy shakers, damage to the branches and final fruit quality issues such as cuts and flesh injury were a problem (L Ferguson et al., 2010). This fruit damage reduced market acceptability, especially of green processed table olives. To solve the issues with mechanical harvesting of traditional orchards, Ferguson et al. (2010) suggested modifying the canopy size and shape of conventional trees and mechanical harvester parameters simultaneously.

Although some olive growers are having some success with trunk shakers, this method has not been widely utilized because the willowy olive trees growth habit prevents the effective transmission of vibrational energy from the trunk to the small distal branches where the fruit is located. To remove fruit with a trunk shaker

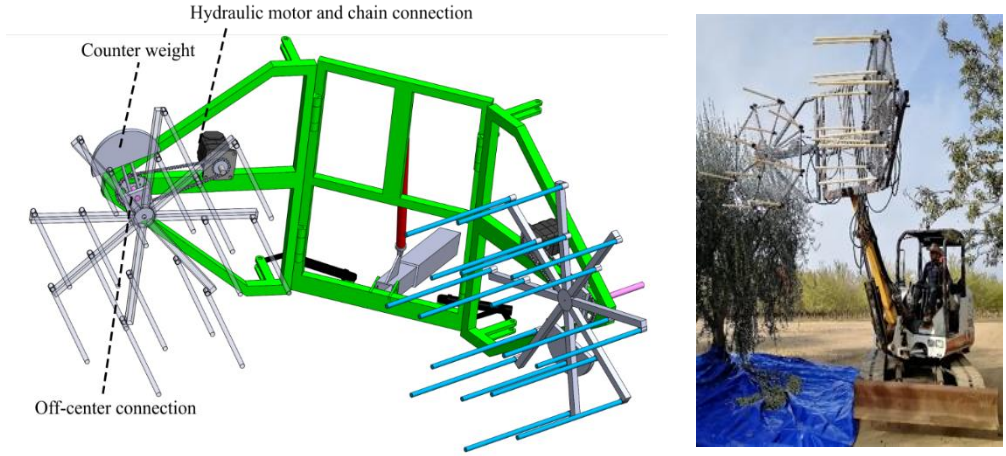


Figure.6.1 UC Merced fruit removal canopy shaking head

requires a large amount of energy and extended duration, which can cause tree damage. Also, for some older orchards, the trunk shaker may not be an option due to the size and shape of the trunk and/or canopy.

Engineers at UC Davis developed a prototype canopy contact shaker that was tested with some success, and which was very similar to the canopy shaker used to harvest Florida juice oranges. Ehsani's group at UC Merced used an alternative design to develop a 50% lighter canopy contact shaker-based fruit removal system that can accommodate larger trees. This system has shown promising results as well. The UC Merced design was able to produce the maximum shaking energy at the fruit level as opposed to the trunk, and hence, less damage to the tree. However, it took a long time to shake each tree.

In part one of this COC (California Olive Committee) funded project, a simultaneous combination of trunk and canopy shaker technologies was tested in 2020. The combined shaking methods demonstrated a higher harvest efficiency compared to using either alone.

This word is the continuation of a previously funded COC project. Figure.6.1 shows the UC Merced canopy shaker fruit removal system. The UC Merced-designed canopy shaker was tested in 2018, 2019 and 2020

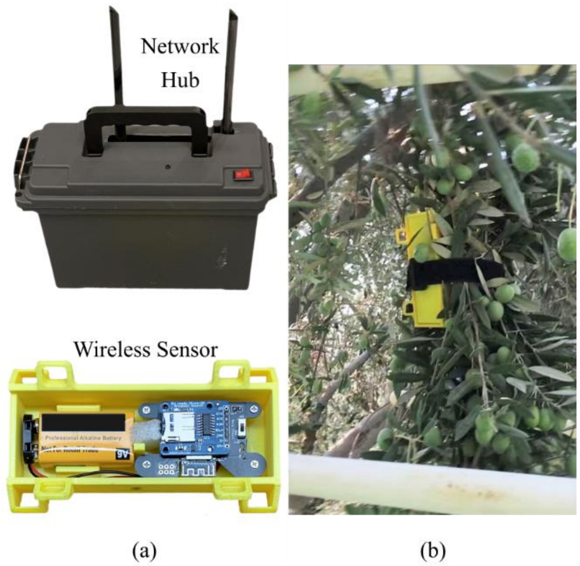


Figure.6.2 Wireless sensor module and network hub (a) and a wireless sensor module installed on olive branches for data collection (b).

6.2 Objectives:

- Study effect of a larger canopy shaker on old and large olive trees.
- To disseminate the integrated knowledge gained through this research.

6.3 Experimental Procedures:

To achieve the objectives of the proposed project, the following specific tasks are planned to be done:

Task 1- To design and construct a very larger side-mounted canopy shaking head that can be attached to a mini-excavator and can accommodate shaking the canopy of larger trees (Figure.6.3).

Task 2- Conduct a series of field tests at one of the collaborating growers to evaluate the performance of the newly designed canopy shaker and use the data to estimate the total yield.

6.4 New Shaker Machine

The new canopy shaker was built in Ehsani’s Lab (Figure.6.4). The new canopy shaker head has a rectangular shape with a height of 8ft and a width of 10ft. The shaker head has a total of 37 mounted Teflon rods. These plastic rods are the contact point between the canopy shaker and the tree. Each rod has 1in diameter and 26in length. A branch shaker was built instead of a trunk shaker as it would be more versatile and compatible to irregular trunk shapes.

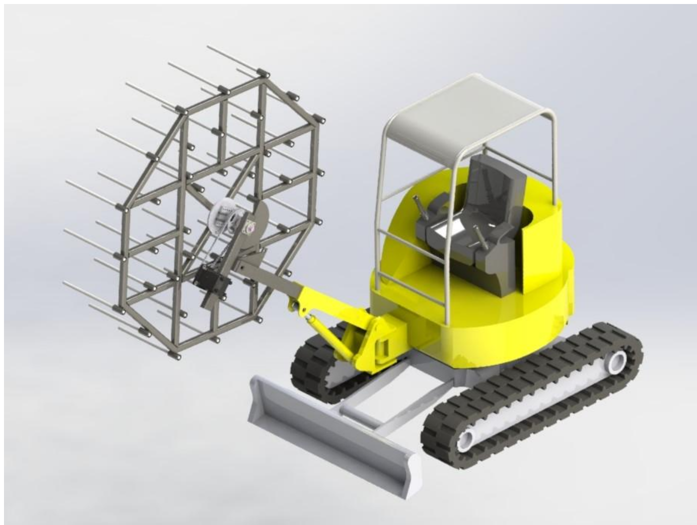


Figure.6.3 Proposed shaker design that includes a side-mounted canopy shaker.

Shaker head has been installed on a Bobcat 337. Figure.6.5 shows the off-center mechanism used to generate circular oscillatory motion. The canopy shaker was set to a 2″ off-center distance, generating an oscillation with a 4″ amplitude.

6.5 Experimental Procedure

This shaker machine was tested in an olive orchard on September 23rd, 2021. The sample trees were topped at 12 and 14 feet in March 2021 by the orchard owner. Four trees were randomly selected from each height category for this experiment. Tarps were used to collect the mechanically harvested fruit. A sample from each tree was sent to a grading lab to get fruit quality data.

An experienced olive harvesting gleaning crew was hired to harvest the fruit remaining on the trees. The manually harvested fruit was weighed and recorded. Harvest efficiency was calculated using equation (6.1).

$$Efficiency = \frac{Mechanically\ harvested\ (lb)}{Manually\ harvested\ (lb) + \ Mechanically\ harvested\ (lb)} \times 100 \qquad (6.1)$$

Figure.6.4 Newly designed canopy shaker built for old large olive trees in California.

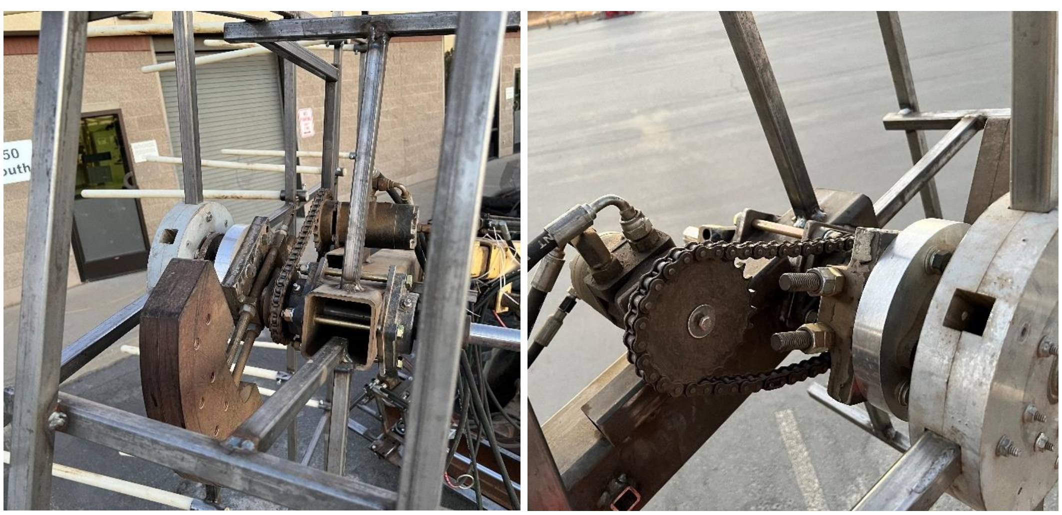


Figure.6.5 Internal mechanism used to generate circular oscillation movement in the canopy shaker.

6.6 Results

Table 6.1 shows the weight of the fruits harvested by the canopy shaker and what was harvested by the gleaning crew. It also shows the harvest efficiency of each individual tree.

Figure.6.6 shows the average harvest efficiency for each category and an average of all the trees.

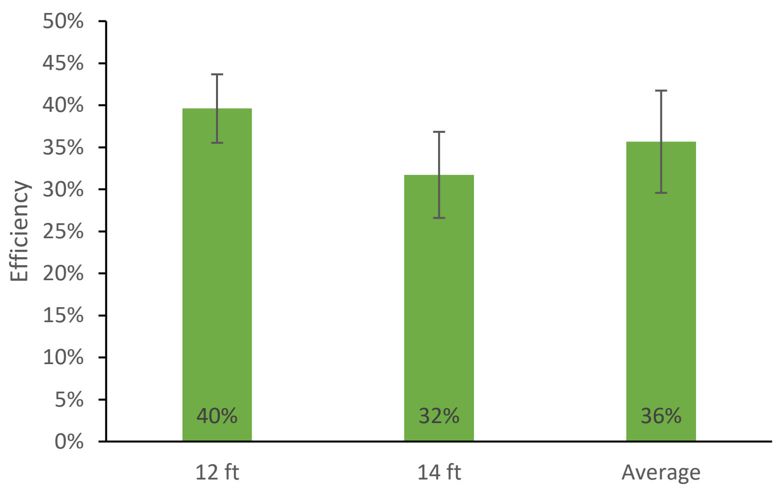


Figure.6.6 Harvest efficiency of trees topped at 12, 14 feet and an average of both.

Table 6.1 Harvest fruit data from each tree.

Tree	Topped height (ft)	Mechanically harvested fruits (lb.)	Manually harvested fruits (lb.)	Total weight	Harvest Efficiency
1	12	53.4	118.4	171.8	31%
2	12	63.6	103.9	167.5	38%
3	12	53.3	104	157.3	34%
4	12	41.2	131	172.2	24%
5	14	83.6	115.4	199	42%
6	14	61.2	95.3	156.5	39%
7	14	60.1	76.3	136.4	44%
8	14	50.1	100.6	150.7	33%

A grading lab has evaluated the quality of harvested fruits, and the results are shown in Figure 6.7. In both samples quality of fruits harvested by the canopy shaker has been higher than the remaining fruits, which have been harvested manually. On the other hand, the overall fruit quality of olive trees with 14ft canopy was higher than the trees with 12ft canopy. This is partly due to the size of fruits harvested from the shorter trees. Figure 6.8 shows the distribution of harvested fruit size from each trial. It shows that shorter trees have produced more sub-petite and undersize fruits compared to the taller trees, this is the main reason the price of the fruit harvested from shorter trees has been lower.

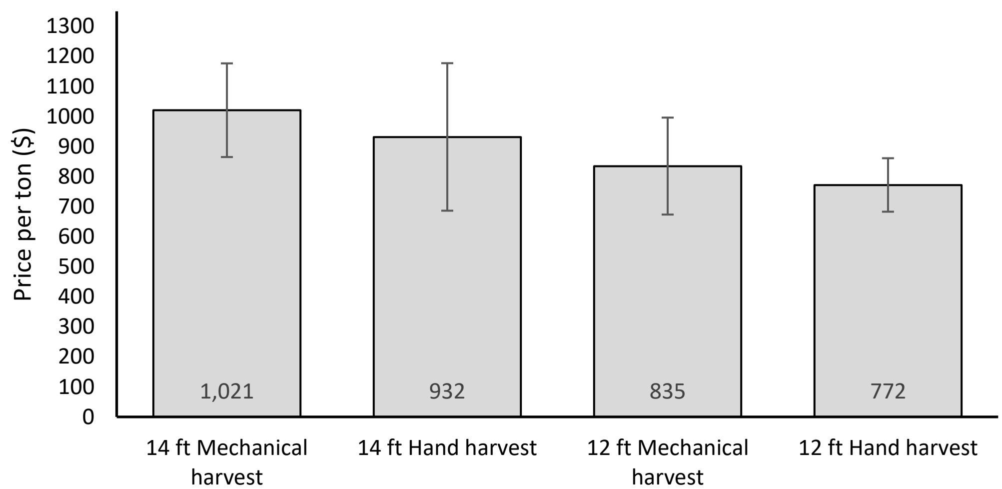


Figure 6.7 Fruit quality results obtained from a grading lab.

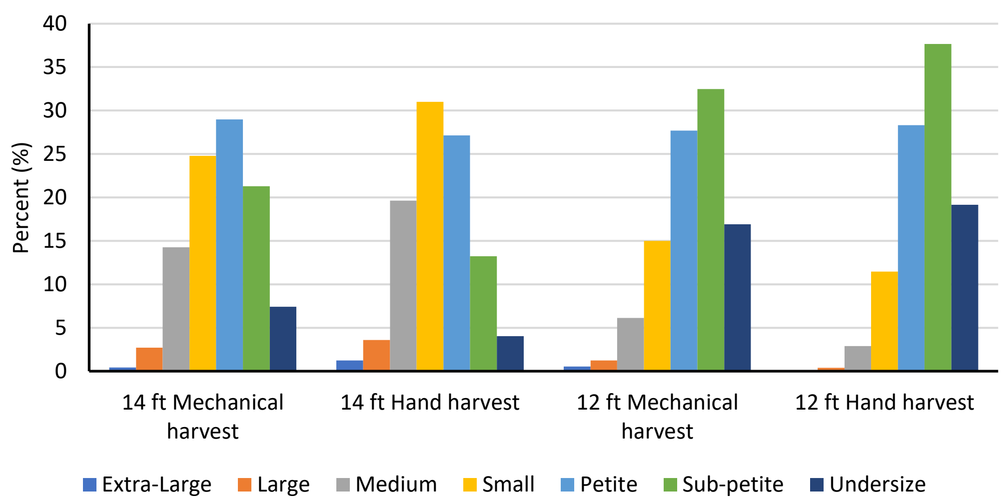


Figure 6.8 Fruit size distribution from each trial.

6.7 Conclusion

A modified canopy shaker design was conceptualized and built based on field observation (Figure.6.3). The new side-mounted canopy shaker is designed for bigger old olive trees which have not been trained for the mechanical shaker. The shaker attachment will allow the machine to go through orchard rows and shake every single tree at the required height.

The shaking head was able to remove most of the fruits where it contacted the canopy. The low harvest efficiency was mostly due to the lack of adjustability of the shaking head itself, which will be addressed in a future design. On the other hand, the harvested fruits showed some degree of damage and bruise. The branch shaker used in the experiment needed some reinforcement to improve its reliability.

The future design needs to have a smaller shaker head with more degrees of freedom for better adjustment. A shaker head with two or three degrees of freedom can be used to increase harvest efficiency. In a future design, the shaking rods need to have padding on them to reduce damage during the harvest.

Chapter 7

Future Work

7.1 Use of Machine Learning in Smart Agriculture

As it gets difficult to find trained and experienced harvesting operators, a new approach is to design a system to observe and learn how an experienced operator harvest the trees. Eventually this method can be used to replace decision making process for a new or non-expert driver. Such a system can also benefit expert drivers as human decision-making is affected by the state of mind and human body physical challenges such as long hours of work. Such a system can deliver constant performance regardless of driver expertise. This can greatly benefit growers to increase their margin of profit.

7.2 Optimize Shake Duration and Smart Controller

To determine the optimal duration for shaking, one can monitor the rate of fruit drop on the catch frame. A fruit drop flow rate sensor can be developed to monitor the rate of fruit drop on the mechanical harvesting catch frame (Fig. 2). A similar device has been developed for yield monitoring of citrus harvesting machines (Ehsani, Grift, Maja, & Zhong, 2009).

The fruit drop rate method based on the Poisson arrival assumption depends on the ability to measure the lengths of the clumps of fruits in real-time. On one side of the sensor, an array of laser beams can be mounted, and on the opposite side, an optical detector can be installed. The size of the pistachio nuts will dictate the distance between the two laser grids. The sensor can be designed to prevent debris from interfering with the sensor.

The developed sensor can also be used later as a part of a closed-loop control system to automatically and optimally control the shaking intensity and duration. In this application, the sensor will measure the fruit drop rate and send the data to a control unit. This unit will monitor the fruit harvest rate and, using an extremum-seeking control algorithm, will generate the optimum shaking intensity for each individual tree. Extremum-seeking control is an appropriate choice for this application as this method does not require a mathematical equation for the dynamics of the system.

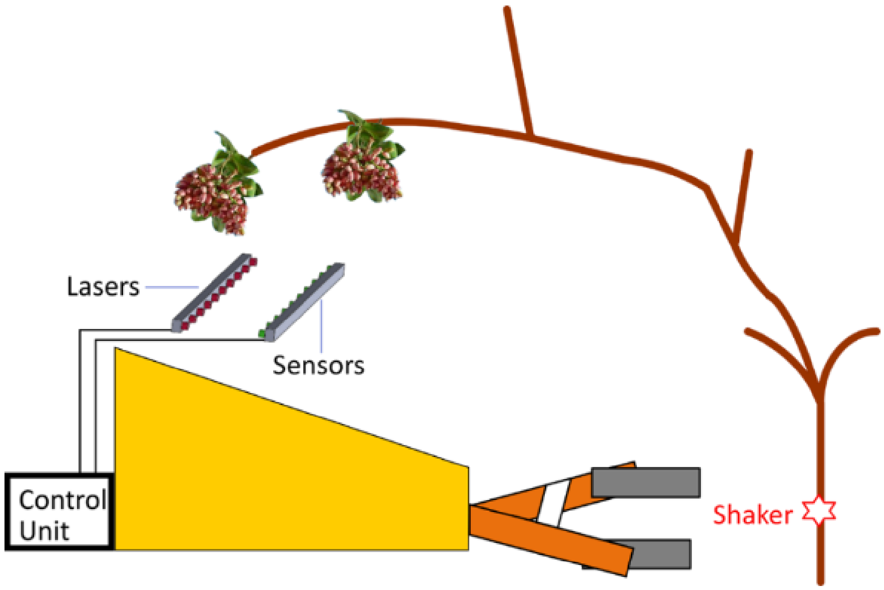


Figure 7.1 A fruit drop rate monitoring sensor mounted on a shaker catch frame

In this method, the output of system $y = f(\theta)$ (fruit falling rate) will be measured. This control system will start to shake a tree using a predefined initial intensity θ and will add a perturbation signal to the initial intensity while measuring the output of the system. If increasing input results in favor of objective (higher output y), then it will update the input θ by $\hat{\theta}$. This loop will continue until the system reaches the maximum possible output (y^*). As the mass of a tree decreases during a shake, the optimum shaking intensity will change; therefore, this control system can track the optimum shaking intensity during a shake using laser-sensor feedback. An accurate initial shaking intensity is essential for the control algorithm to perform effectively.

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