DEVELOPMENT OF A SELF-PROPELLED CITRUS CANOPY SHAKER FOR HARVESTING SEMI-DWARFED HIGH DENSITY PLANTINGS

By

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To Almighty Allah, for his boundless generosities and boundless support in my life, and also to my wife and children for their sincere love and patience

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TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

LIST OF FIGURES

LIST OF OBJECTS

LIST OF SYMBOLS

A_c	The area of the cross-section of the materials used ($inch^2$)
S'_n	The actual endurance strength (psi)
C_m	The material factor
C_{st}	Type of stress factor
C_R	The reliability factor
Cs	The size factor
S_n	The endurance strength (psi)
S	The section modulus ($inch^3$)
N	The design factor
S_u	The tensile (ultimate) strength (psi)
S_y	The yield strength (psi)
M_m	The mean bending moment (lb-in)
M_a	The alternative bending moment (lb-in)
K_t	The stress concentration factor
D	The diameter of the materials used (inch)
F_m	The mean force (lb)
F_a	The alternative force (lb)
F_{max}	The maximum force (lb)
F_{min}	The minimum force (lb)
S_{sy}	The yield strength in shear under actual conditions (psi)
S'_{sn}	The endurance strength in shear under actual conditions (psi)
π	Pi, a mathematical constant

M_{max}	The maximum bending moment (lb-in)
M_{min}	The minimum bending moment (lb-in)
T	The shaft torque (lb-in)
M	The shaft bending moment (lb-in)
D_f	The branch diameter at the point of the force effect (inch)
I	Moment of inertia ($inch^4$)
L_{bf}	Length of the branch to the point of force effect (inch)
F	Pull force that affected on tree branch (lb)
E	Modulus of elasticity (psi)
M	Bending moment (lb-in)
y	Beam or branches deflection (in)
w	Force that affected on the beam (lb)
x	The beam length from the fixed end (inch)
ℓ	The length of beam, branch, or the turn buckle links (inch)
c_1	Constant value of the beam deflection equation
c_2	Constant value of the beam deflection equation
δ_y	The ultimate vertical deflection of the clamped-free beam (inch)
δ_{ymax}	The maximum deflection (inch)
ℓ_o	The original length of the tree limbs before applying the force (inch)
$\Delta\ell$	The change in the length of the tree limbs after applying a pull force (inch)
a_T	The resultant of the magnitude of the acceleration data (g)
a_x	The magnitude of the acceleration at x axis (g)
a_y	The magnitude of the acceleration at y axis (g)
a_z	The magnitude of the acceleration at z axis (g)

r	The radius of the crank (inch)
θ	The angular displacement of the crank (radian)
ϕ	The angular displacement of the shaking beater (radian)
a	The shaking beaters regular amplitude at the jointing point of the shaking beater with the turn buckle (inch)
A	The amplitude at the shaking beater free end (inch)
ℓ_1	The length of the shaking beater to the jointing point of the beater with the turn buckle (inch)
ℓ_2	The length of the shaking beater from the jointing point of the beater with the turn buckle to the beater free end (inch)
L	The original length of the shaking beaters (inch)
$\dot{\theta}$	The crank-shaft angular velocity (rad/sec)
S_a	The typical beater's speed at the jointing point (a) of the beater and the turn buckle link (inch/sec)
S_A	The bold speed of the shaking beater at the beater free end (inch/sec)
F_d	The citrus fruit dislodgement percentages (%)
N_d	The number of the dislodged fruit (count)
N_r	The number of the fruit remaining on the citrus tree (count)
Y	The expected overall yield production of the citrus field (ton/hectare)
w_t	The absolute total fruit mass of each citrus tree separately (lb)
$a \times b$	The distance between the citrus trees lines (ft) and the distance between the citrus trees on each row (ft)
Hc	The overall operations cost of the mechanical harvesting ($/hr)
P_M	The price of the mechanical harvester ($)
Y_H	The predicted yearly operation hours (hr/year)
M_L	The life-expectancy of the mechanical harvester (year)
R_i	The rate of interest (%/year)

R_t	The rate of tax (%/year)
R_{rm}	The rate of the mechanical harvester maintenance (%)
L_f	The lubrications factor
P_w	The harvesting machine power (kw)
F_p	The price of fuel ($/gal)
F_{cns}	The consumption of fuel (gal/kw.hr)
L_{ms}	The labor monthly salary ($)
O_{mo}	The predicted average of the operation hours for each month (hr/month)
Mfd1	Lowest forward speed of the harvester (mi/hr)
Mfd2	Highest forward speed of the harvester (mi/hr)
Tw1	Default width of the internal tunnel of the citrus harvester (in)
Tw2	Second width of the internal tunnel of the citrus harvester (in)
Bp1	First beaters position by 12 inches of the turn buckle length (in)
Bp2	Default beaters position by multiple lengths of the turn buckles (in)
Bp3	Third beaters position by 16 inches of the turn buckle length (in)
Shs1	Lowest beaters shaking speed (inch/sec)
Shs2	Second beaters shaking speed (inch/sec)
Shs3	Highest beaters shaking speed (inch/sec)

Abstract of Dissertation Presented to the Graduate School
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The harvesting field trials pointed out that the harvesting machine's forward speeds had a significant effect on the percentage of grapefruit harvested by canopy shaking. The highest average detachment percentage was 80.03 % at the lowest forward speed of 0.62 mi/hr, while the minimum detaching percentage 72.98 %, was the result of the machine forward speed of 1.42 mi/hr. The initial trials also found that changing the lengths of the turn buckles to adjust the shaking beaters position on the canopy shaker significantly affected the grapefruit detachment percentage at the 10 % level of significance. The third beaters' position (turn buckles length 16 inches) had the highest average of 87.97 %. The beaters shaking speed also significantly affected the grapefruit detachment percentage at the 10 % level of significance. By increasing the beater shaking speed from 56.50 to 73 in/sec, the grapefruit detachment percentage increased up to 79.72 % (the maximum average). Also, by increasing the length of the additional beaters, the maximum grapefruit detachment percentage increased to 93.29 %. On the other hand, the average magnitude of the acceleration (g) among the tree canopy branches increased significantly (average magnitude 8.65 g) when the shaking beater number was increased from 14 beaters to 26 beaters.

Looking at the previous findings, this study recommends operating the new prototype citrus harvesting machine either at forward speed 0.62 mi/hr or 1.42 mi/hr, with the turn buckle length at 16 inches, and the beaters' shaking speed at 73 in/sec. These configurations resulted in higher grapefruit detachment percentages, with averages 93.56 % and 93.52 %, respectively. Finally, some minor visible damages, such as splits to some branch crotch angles, have occurred during grapefruit harvesting due to impact of the harvester's beaters with the branches underneath tree canopies. However, when operating at a harvesting width of 69 inches, which was utilized during May 2013 canopy shaker field operations, no damages to the grapefruit tree trunks were observed. The trunks were unaffected by the harvester's shaking beaters unless the harvester's operator could not maintain the main trunk of each tree as the center of the harvesting direction.

CHAPTER 1
INTRODUCTION

General Information

The United States of America is second in terms of global citrus crop production (13 million tons of citrus crops in the 2007-08 season), only to Brazil (15.912 million tons of orange fruits for the season of 2007-08). In the United States, the State of Florida leads citrus production with approximately 9,119,000 tons of fruit (203.8 million 90 lb boxes) during the 2007-08 season, which is approximately 70 % of the total United States citrus crop. Meanwhile, the second leading producer was California with 3,470,000 tons of fruit production during the same harvest season (the United States Department of Agriculture (USDA) and NASS, 2009). The State of Florida has more than 12 thousand citrus producers, who cultivate 569 thousand acres of citrus farmlands, with almost 74 million citrus trees (Florida Department of Citrus, 2008).

During the early 1950s, Florida was the hub for the citrus industry, leading to a heavy demand for manual citrus harvesting. Toward the end of 1960s and early 1970s, manual citrus harvesting became a less economically viable solution, as local labor costs had increased, and there was shrinking labor force (Whitney, 1995). As a result, expenditures for manual harvesting increased from $ 0.65 per box in 2000 to $ 0.91 per box in 2010, assuming estimated laborers' productivity at eight boxes per hour (Roka, 2010).

Thus, due to the increase in the cost of manual harvesting, interest in mechanization of citrus harvesting increased significantly. Mechanical citrus harvesting, by shaking either the trunk or canopy, has been the most successful and most commonly used harvesting approach in Florida citrus production. Thus, with citrus harvesting mechanisms still under development, and increasing cost of labor in citrus harvesting, efforts in mechanical harvesting have been devoted to developing a method of mechanizing citrus harvesting by new mechanical approaches.

Consequently, when using mechanical harvesting systems, estimates suggest that well over 50 percent of the total cost of citrus harvesting will be conserved (Brown, 2002 and 2005).

In the late 1950s-early 1980s, interest in mechanical harvesting of citrus began to grow, due to the increase in the production of citrus and lack of access to citrus hand harvesters. But by 1990 in Florida, none of the early developed mechanical harvesting technologies had been implemented, due to the freezes, hurricanes, and spread of some citrus trees diseases during the 1980s, and the fear of the harvesting machines contributing to the distribution of these diseases (Whitney and Harrell, 1989).

Since 1994, with a renewed confidence in mechanical harvesting, the Florida citrus industry and the FDOC became more interested in developing mechanical harvesting, especially for processed oranges, since the Florida growers were tending toward higher density planting of citrus trees (65 to 180 trees per acre). This effort was intended to decrease the citrus harvesting cost and increase labor productivity. During this period, eight harvesting systems were manufactured, depending on the citrus tree canopy arrangement. Some of these 8 harvesting systems achieved 10 % to 75 % savings of harvesting costs and more than 5 times labor productivity increases (Brown, 2005). So, the number one priority of the citrus industry was the high harvest laborers' cost.

In addition, because the Huanglongbing (HLB) bacteria, known as a major citrus greening disease which can cause damage to citrus trees, was reported in China in 1919, and then in Florida in 2005, the citrus production economy in Florida was adversely affected. This disease causes fruit to drop and trees produce smaller fruit, thus decreasing the tree productivity. There is no technique to eradicate the greening disease, but some practices for growers that have emerged to reduce spread of the disease, such as management of grove greening (UF-IFAS, 2014).

Recently, the use of small citrus trees with high density is intended to be the standard over Florida citrus farmlands. So subsequently, the further development of citrus harvesting mechanisms promises to be a continuing empowering agent of economic viability.

Even though development of mechanized harvesting methods for citrus trees has been going on for 30 to 40 years on traditional tree sizes, the primary purpose for this research was to design a reliable, self-propelled, over the top canopy shaker machine for harvesting citrus trees grown in high density hedgerows with size-controlling citrus rootstocks (trees are grown at an average height less than ten feet).

Research Objectives

The main objective of this research is to design a canopy shaker prototype for the high density semi-dwarfed citrus trees. These trees are planted in a high hedgerow density. The specific designated core sub-objectives included in this research are listed below:

1. Design and build a prototype of an innovative, self-propelled, over the top citrus harvesting machine using canopy shakers, which can be utilized to harvest citrus trees with canopy height of 10 feet or less.
2. Test that prototype to assess the optimal performance under existing citrus grove conditions. The test assessment includes:
    a) Determine the optimal shaking frequency, and shaking time to obtain best fruit removal.
    b) Determine the optimal shaker beater configuration and stroke for best fruit removal.
    c) Monitor the influence of shaker stroke, frequency, and beater design on the tree canopy excitation.

CHAPTER 2
LITERATURE REVIEW

Overview

Since the mid-1950s there has been a growing interest among Florida citrus growers to change the citrus harvesting method by using new innovative mechanical techniques. Mechanical harvesting techniques could reduce the manual work force (harvesting laborers), which previously has greatly influenced the cost and time required for harvesting.

Hence, several fruit harvester manufacturers became involved in developing mechanical harvesting technologies. These manufacturers include: Korvan Industries Inc., Lynden, WA, and OXBO International Corporation, Byron, NY (Peterson, 2003), Littau Harvester Inc., Blueberry Harvester, Stayton, Oregon, Weygandt Inc., Canby, Oregon, and BEI International, LLC, South Haven, MI (Peterson and Takeda, 2003), Everglades Harvesting & Hauling, Inc., LaBelle, FL, Rectangle Harvesting, LLC, Avon Park, FL, Sam Adams, Felda, FL, T & S Harvesting, Felda, FL, and Mutual Harvesting, Inc., Lakeland, FL (Futch and Roka, 2005). These companies began competing in the development of the fruit harvesting systems as shown in Figures 2-1, 2-2, and 2-3.

Moreover, according to previous scientific research, methods for the development of harvesting machines were dependent on three primary methods for removing ripe fruits from the citrus trees. These three methods were a) shaking the trunks and individual limbs of trees to extract the ripe fruits, b) shaking the whole tree canopies to extract the ripe fruits, and c) manual or robotic picking method (selective harvesting). These three methods are described briefly in the following topics:

Excitation of Trunks and Individual Limbs of Trees to Extract the Ripe Fruits

A sweet cherries harvester for fresh market, using a catch frame with inclined conveyer and a single hydraulic arm shaker with a rapid-displacement actuator (RDA) method, was developed by Peterson and Wolford (2001). Later, a sweet cherries harvester utilizing two long hydraulic arms (joysticks) with the RDA method was designed by Peterson et al. (2003) to impact cherry tree limb and trunk displacement acceleration. Detachment of the sweet cherries depended on cherry tree limbs and trunk oscillations. From a single RDA harvester, the sweet cherries harvested ranged between 85 to 92 %, with 2 to 6 % fruit injury. Whereas, 90 % of the cherries fruit were detached, at a harvesting rate between 85 and 158 trees per hour, for the two identical RDA harvesters mounted on each end of the cherry harvester.

Bohannon (1969) designed a citrus fruit harvester under U.S. Patent Number 3,485,025, filed on December 9, 1966, for fruit removal by using oscillation of notched rods (three rigid rods and four dynamic rods), which were mounted on a parallel horizontal platform with oscillations between 1,000 and 5,000 times per minute. These rods were placed on a single boom long arm, with fruit conveyer apparatus. Productivity of between 400 to 500 boxes per day was obtained by this harvester.

Erdoğan et al. (2003) reported an apricot harvester and its performance, which used a single hydraulic limb shaker in Turkey’s farmlands. The long shaker arm was 3.34 meters in length and 8.5 cm in diameter. A hydraulic motor, included in the design, was used to furnish oscillations to the arm for tree limb shaking. The apricot limb oscillations were between 20 to 60 mm amplitude, for 5 seconds duration, with frequencies of 10 to 20 Hz. Optimum apricot detachment, without tree limb or bark injury, required 5 second oscillations at 15 Hz frequency, and 40 mm of arm amplitude. In contrast, 400 minutes of labor were required to manually harvest an apricot tree.

In Spain, during the harvest of 2003-04, a trunk shaker, which was mounted to a tractor (76 kw), was investigated to detach olives from the olive trees, using an unbroken oscillation (one periodic oscillation) and coupled-short-periodic oscillations (two periodic oscillations). Using that tree trunk shaker with tree acceleration of 210 m/s^2 and oscillations between 20 to 25 Hz, the two periodic oscillations (10+10 second) detached the olives within 20 seconds of continuous shaking. Furthermore, 90 % detachment of the olives was achieved using 13.3 seconds of oscillation time. Oscillation time of more than 16 to 18 seconds was not effective on olive detachment, which showed that a long period of oscillation was unfavorable. Also, by the end of olive harvesting season, 13.3 seconds of oscillation used at the beginning of harvesting season had diminished to two seconds of the canopy oscillation time (Blanco-Roldán et al., 2009).

In the 2011 citrus harvesting season, the Oxbo olives harvester (engine 173 hp) was adapted to harvest Florida small, young orange trees. Overall machine dimensions were 252 inches (length) and 143 inches (width). Also, dimensions of the machine internal tunnel were 54 inches (1.37 m) of the tunnel width and height from 108 to 138 inches (2.74 - 3.50 m). The primary results of these harvesting trials indicated an appropriate fruit picking rate up to 95 %, but the machine needs to be adapted to harvest citrus tree canopy planted with a high density (Ehsani and Khot, 2012).

Loghavi and Mohseni (2006) investigated limb vibrations on lime fruit removal by developing an adjustable long beam shaker (1.2 to 2 meters long) attached to a tractor, as shown in Figure 2-4. The clamper that works as fingers (has two fingers) grasp the lime limbs to transfer vibrations to the lime fruit. The design mechanism has been tested using three shaking frequencies (5, 7.5, and 10 Hz) and three shaking extensions (40, 80, and 120 mm). The force of

1.93N was used for ripe limes and a 13.61 N force for unripe limes. With shaking frequency of 10 Hz and shaking extension of 120 mm, all the lime fruits were removed (100 %). Comparatively, a shaking frequency of 10 Hz with 80 mm of beam extension resulted in 98.5 % of the lime fruits being harvested.

Peterson and Bennedsen (2005) described a rapid displacement actuator (RDA) apple harvester that utilized a single and three rapid impulses for apple detachment on the long and short limbs of apple trees (grown in spring of 1999). It was implemented on a Y-trellis tree prototype using a hydraulic joystick (a long horizontal reaping arm (78 inches) with 2 inches stroke displacement). The fallen fruit landed on the top of a padded conveyer. A total of 53 to 72 % of those apples were injury free quality. Both long and short tree limbs of those apple trees showed similar numbers of fruit detachment and fruit quality.

Peterson and Wolford (2003) developed an apple harvester that included two identical limb harvesters for small apple trellises, as represented in Figure 2-5. Each limb harvester utilized a long hydraulic arm (a long joystick) for the apple trunk oscillations and collecting conveyer. The rapid displacement actuator method was used for apple detachment. From the 95 % of total apples detached, between 86 and 95 % of the apples were retrieved using that harvesting method. Of the eight varieties of apples that were studied, fresh market graded four types of apples between 86 to 90 %. Less than 5 % of the apples were left on the apple trees and less than 11 % of the apples were lost to the ground.

Torregrosa et al. (2006) presented an analysis report for different mechanical harvesting systems used for apricots fruits in Spain throughout the 2001, 2002, and 2003 seasons, aimed at reducing harvesting time and costs. The different harvesting systems were used to snap the fruit by using an apricot trunk shaker with an inverted catching frame (upside down umbrella) for

fruit to fall on. The trunk shaker and catch frame, and a storage container were hung from a tractor (50 kw) on a three point hitch. The continuous trunk shaker and catch frame were pulled by the tractor with forward speeds between 0.7 and 2.5 km/h. A 13.7 to 22.5 Hz frequency was required to dislodge the apricots fruits with acceleration between 51 and 590 m/s^2. These harvesting systems were compared to a manual tree shaking method by laborers' hands. The apricots fruits harvested by machine detached in less than 2.4 seconds, which was less than the time required to harvest the fruit by hand laborers. Besides, costs of harvesting was reduced from 0.107 euro/kg for manual harvesting to between 0.006 and 0.039 euro/kg by operating those mechanical harvesters.

Torregrosa et al. (2009) presented the comparison of orange and mandarin harvesting, during the harvesting seasons from 2006 to 2009 in Spain, comparing a trunk shaking by an extendable long arm with clamper, two long arms (2 and 1.8 meters) and a frequency of 18-21 Hz, with manual harvesting. The frequencies of 9, 15, and 25 Hz were required for the orange trees while the mandarin trees required frequencies of 7.4, 14.6, and 21.6 Hz. The percentages of fruit detachment were higher with the mechanical shaking (73.25 %) than the manual shaking of the tree limbs (55.67 %). Also, the shaking time of 4 and 5 seconds at a frequency of 15 Hz were adequate for the optimal percentage of fruit removal (average 65 % of the fruit removal).

Shaking the whole Tree Canopies to Extract the Ripe Fruits

A fruit detachment machine with conveyer apparatus was invented by Visser (2001) and Schloesser (2005), which are shown in Figure 2-6 and Figure 2-7, respectively. These harvesters were designed to detach the fruit from the tree canopy and have it fall onto the conveyer apparatus. Shaker components typically included a rigid single mast (vertical long shaft), rotator cranks, movable arms that extended and retracted in horizontal, and six pairs of free twistable nipper disks. Each of the three pairs of nipper disks engaged each tree at the same time

meanwhile the other three pairs of the nipper disks retracted to rearward (on the opposite side; close to the vertical mast). Furthermore, each single nipper disk had sixteen sticks (fingers) displaced radially at equal angles with linear displacement action provided by cranks. The resulting labor productivity significantly reduced harvesting time and cost. Likewise, Briesemeister et al. (2006 & 2008) developed a fruit harvester (canopy shakers) with fruit dropping on the ground (Figure 2-8), and Briesemeister (2002) developed a fruit harvester (canopy shaker) with a retractable conveyer to recover the removed fruit.

A prototype self-propelled harvester machine with a conveyer belt was developed to harvest six kinds of apples from apple trellises that had a small horizontal H canopy, during the 1987 season in New Zealand, as depicted in Figure 2-9. For the canopy shaker of this harvester, six shaking whorls were mounted on an isometric pair of transverse shafts. Each transverse shaft had three whorls with identical flexible pinnatisect edges for reducing injury to the apples. The shaking shafts with the flexible whorls were oscillated using a hydraulic motor in order to horizontally excite the apple canopy, with oscillations between zero to 10 Hz and 26 mm of displacement. The harvesting rate was four trees per hour which was achieved by 0.3 km/h of harvester forward speed. Optimal apple detachment was accomplished at oscillations between 4 to 6 Hz. Furthermore, the apple quality ranged between 42 to 95 %, and the apple detachments were measured between 89 and 97 %, with low apples injuries approximated between 3 to 31 % (Láng, 1989).

A citrus canopy air shaker is designed to dislodge the citrus fruit as pictured in Figure 2-10. A Propeller fan was built with a hydraulic lifting apparatus for the tall tree canopy. With an air velocity of 125 mph, 1500 rpm of fan speed, 22.2 N of the fruit dislodgement force, and a forward traveling speed of 1mph, the average of fruit dislodgement with an abscission chemical

application was 97 % of fruit removal, and a harvesting speed of 170 trees per hour (Coppock and Donhaiser, 1981).

A blueberry harvester that involved two inclined symmetrical spokes-drums has been developed for fresh blueberry market, as shown in Figure 2-11. Six spiral catchers are arranged on each mast-drum, and each spiral catcher was built with 24 uniform 480 mm length sticks. The two spokes-drums were angled in 45º on the horizontal side and swung by a harvester gearbox. The sticks' length (3.80 cm) penetrated into the blueberry canopy 10 cm. The positioning of the inclined symmetrical spokes-drums decreased the fruit losses to 44 %, plus the blueberry harvested was found to be fresh market quality (Peterson et al., 1997). In another evaluation, the BEI International blueberries harvester that is shown in Figure 2-3 was utilized to harvest dwarfed citrus trees in the 2011 harvesting season of south Florida. Overall machine dimensions were 252 inches (length), 119 inches (width), and 131 inches (height). Also, dimensions of the machine tunnel were 54 inches of the tunnel width and height from 84 to 98 inches. The primary harvesting trials resulted in a proper harvesting rate up to 95 %, but the machine needed to be adapted to harvest citrus tree canopy planted with a high density (Ehsani and Khot, 2012).

In addition, Peterson and Takeda (2003) developed a harvester machine that was designed in 2000 for thornless blackberry (Figure 2-12). The new harvester had two isometric spokes-drums shakers. Each drum had eight spiral catchers, which were mounted on a 7 inch (18 cm) drum. Furthermore, 24 shaking sticks were attached on each spiral catcher. The blackberry harvester also had a conveyer to hold the detached fruit. Once the blackberry fruit was detached, it was sorted via the laborers hands. Spoke penetration into the blackberry trees canopies was from 4 to 6 inches (10 to 15 cm). The trees canopies were oscillated at frequencies from 5.8 to 7.9 Hz, with 105 to 140 N-m of applied torque, and the harvester forward speed was 0.5 mph

(0.8 km/hr). However, this eastern thornless blackberry harvest was not successful for blackberry fresh market quality, due to the low percentage of fresh market rating between 36 and 56 %.

Crunkelton (1992) invented a fruit harvesting mechanism using lengthwise dislodgement sticks mounted to a vertical mast that was mounted on a tractor, publicized in U.S. Patent Number 5,161,358 filed on July 8, 1991. By using retractable and extendable sticks, the tree canopy was engaged by the harvester and the fruits were removed from the tree branches without injuries (fruits fell to the ground directly).

De Mendonça Fava et al. (2005) reported a crop harvester with a piloting system strategy, which was described in U.S. Patent Number 6,959,527 B2 filed on February 21, 2003, and deployed in Brazil. The 56 radial shaking spokes were arranged on a vertical rotor drum. When the associated position sensors detect the tree canopy, two actuators were used to modify the vertical rotor drum and picking spokes positions. This invention determined the harvester position and its trajectory around the tree canopy, so that the fruit harvester could to achieve exceptional performance.

Peterson et al. (1989) reported the description of a shaking system for a small continuous fruit harvester used for harvesting blueberry and grape, which was described under U.S. Patent Number 4,860,529 filed on August 8, 1988. That harvester utilized a double spokes-drum which vibrated the spokes (24 radial sticks set on equal angles for each spokes-disc (6 spokes-discs)) with varied canopy penetration displacements (0.15, 0.27, and 0.63 inches). In addition, the two spoke-drums vibrated in parallel to the spoke-drums revolution and the harvester travel along trellis rows with three different types of trellis canopy. Contrariwise, Christie and Winquist (1967) had described another berry harvester utilizing spokes-drums that was invented under

U.S. Patent Number 3,325,984 filed on October 28, 1963. These spokes-drums vibrated perpendicularly to the spokes-drums revolution.

Peterson and Miller (1989) indicated an apples harvester that was designed by the Appalachian Fruit Research Station (USDA) as shown in Figure 2-13. That harvester integrated small vertical sticks to dislodge two kinds of apples from the trees by using the canopy pressing method. These apple trees were shaped on trellises that had a T-shape. The sticks penetration into the apple tree canopy was 100 mm per second with 34±5 N of pressing force on each stick. The sticks, with diameters of 13.7 mm and 7.6 mm, were arranged on a rectangle frame of the canopy shaker. The detached apples were collected at efficiencies between 88.8 to 97.5 %. The percentage of injured apples was 1 to 7.4 % bruised, and 7.6 to 21 % cut and punctured.

Peterson (1998) developed a vertical continuous tree canopy shaker to harvest a tall orange tree canopy. It included two designs. The first involved a pair of spokes-drum shakers as presented in Figure 2-14. Each mast drum had six horizontal spokes-sets arranged on a vertical shaft, with 16 radial spokes arranged on each spoke-set at equal angles. The spokes were inserted into the orange tree canopy to a depth of 39 inches, with 10 inches of spoke displacement, and spoke oscillation frequency of 4 to 5 Hz. The continuous pair spokes-drum canopy shaker was dragged by a tractor at forward speeds between 1.4 and 3.2 kph, with 71 to 91 % of the oranges detached to the ground. The second harvester was designed to harvest oranges trees more than 13 ft (4 m) in height as displayed in Figure 2-15. The continuous two spokes-drums had eight spokes-sets (spokes nippers) spaced on each mast drum. Each spoke-set had 16 radial sticks arranged at equal angles. 46 inches of the sticks were inserted into the orange tree canopy with 10 inches of the horizontal stick displacement and up to 5 Hz sticks oscillation. A conveyer was added to this harvester to catch and transport the detached fruit. It was also pulled by a hitch

point on a 90-Hp tractor. This harvester realized 83 % detachment of the oranges using sticks oscillation of 5 Hz, while 80 % of the fruit was removed and collected when the sticks oscillated at 4.7 Hz.

The canopy shaker described by Hosking (2002) was invented under U.S. Patent Number 2002/0062635 A1 & Number 6,425,233B1 filed on November 29, 2000 (Figure 2-16). Another, described by Daniels (1999), was invented under U.S. Patent Number 5,946,896 filed on January 23, 1998. These canopy shakers included two fruit detachment sections (four vibration fruit detachment boards) as shown in Figure 2-17. Each board had 18 to 28 vibrating sticks mounted in parallel. The pairs of fruit detachment sections were swung using a hydraulic motor. Furthermore, these assemblies were mounted onto a single long hydraulic arm.

Dealing with Citrus Fruit Directly for Choosing and Picking (Selective Harvesting)

A prototype of a robotic citrus fruit gripper that utilized fruit vision and robotic picking system (robotic arm), depicted in Figure 2-18, was described by Hannan and Burks (2004). For this design mechanism, the citrus fruit was selected depending on the fruit shape and its color, and the robotic arm pulled the citrus fruit from its place in the tree canopy.

Harrell et al. (1989) described a fruit picking system to harvest the fruit from trees by using a robot. The movement of the robot, in the process of picking the fruit from the tree, was controlled by taking an image of the fruit, localizing position, and then using servos to move into position to harvest.

Lee et al. (2006) developed a citrus harvester to detach the orange stems individually by using an automated and robotic harvester concept. The harvester prototype contained three pneumatic actuators (with orange stems cutter) that were mounted onto the movable frame of a forklift machine. With this concept, 84 % of the oranges were collected without significant

injuries. Moreover, Sivaraman (2006) designed and developed a fruit pulling arm robot with an electro-hydraulic control system for citrus fruit picking (Figure 2-19).

An Overview of the Pragmatic Differences of the Mechanical Harvesting Machines

Recently, in Florida citrus farmlands there are three harvesting systems being used to harvest citrus fruit. One of them is a trunk shaker, and the others are citrus canopy shakers. One with a catch surface used a pair of self-propelled continuous canopy shakers, and the other shaker unit was drawn by a tractor. These mechanical harvesters were designed to reduce the use of hand laborers and thus the cost of fruit harvesting. The first system's operation depends on trunk oscillation by a long clamp arm that sends oscillations to the tree's trunk for fruit detachment. Meanwhile, both of the canopy shakers have spokes mounted on a nipper disk that penetrates into the citrus trees canopies to remove the citrus fruit, as shown in Figures 2-20, 2-21, and 2-22 (Hannan and Burks, 2004; Futch and Roka, 2005; and Futch et al., 2005).

Citrus harvesting machines were investigated throughout the harvesting season of 1996-1997 by Whitney (1999). The citrus harvesting was carried out with a tree canopy shaker mounted to tractor, and a trunk-shaking harvester with fruit capture surface, which were used to harvest one side of the tree row. 55 to 95 % of the oranges were removed from tree canopies by the canopy shaker (with or without fruit catching frame), which used force detachments of 26 to 102 N and 4.5 to 5 Hz shaker frequencies. 84 to 94 % of oranges were detached by using a trunk shaking harvester, with catch frame, which used force detachments between 69 and 115 N, 10 Hz trunk shaker frequency, and 5 cm of shaker displacement.

In Florida, fruit harvesting laborers costs were predicted to be between 1.40 and 1.80 dollars per box. Whereas, fruit harvesting expenses with mechanical harvesting were reduced by more than 50 %. Besides, the advantage of citrus mechanical harvesting was illustrated by contrasting the two widespread harvesting systems that were in use in Florida citrus farmlands

throughout the 1999-00 & 2002-03 seasons. A trunk shaking harvester, with catch frame, averaged a harvest speed of 185 trees/hr. Florida citrus produces also used a continuous canopy shaking harvester, with catch frame, achieving a harvest speed 310 trees/hr. Performance results showed 95 % of fruit removal and 91 % of fruit recovery by using the continuous canopy shaking system, while fruit removal by the trunk shaking system achieved 94 % with 89 % fruit recovery. Both systems achieved 100 boxes per an hour more than the laborers productivities (Roka and Rouse, 2004).

By using the continuous canopy harvesting system and trunk shaker with catch frame, the harvesting labor productivity increased over 5 to 15 times, and the citrus harvesting costs was decreased by 50 to 75 % (Brown, 2002, and 2005). Furthermore, Sanders (2005) showed that the rate of harvesting fruit trees per hectare using canopy-shaking harvester was more than 15 times greater than using manual laborers, and more than 2 to 3 times the rate of the trunk shaking harvester.

Analysis of the Vibration during the Period of the Mechanical Harvesting

Udumala Savary (2009) and Udumala Savary et al. (2011) conducted a study of the forces of vibration on the citrus tree canopy exposed to the force of the mechanical harvesting (TDCS machine) using an instrument that measures the force required for the citrus fruits to be removed. That device was placed on random citrus tree branches (small & large of Hamlin and Valencia trees) and on the citrus fruits to study the impact of the resistance of citrus fruits to the vibration forces of the mechanical harvester, as shown in Figure 2-23. The fruit detachment force (FDF) that is required for citrus tree harvesting was measured by using a tiny low g accelerometer (Freescale MMA7260Q), which had a sensitivity of up to ± 6 g, with supply voltage in the range of 2.2V and 3.6V, a single-pole filter, a sleep mode 3μA with XBee-PRO RF module, and a small sensor (XBee-PRO DigiMesh 2.4 GHz), which was employed as a data

acquisition device between the PC and the accelerometers. These apparatuses were attached together, with a load amplifier, and coupled to a USB port on a PC. For the FDF application, the operating variables examined by this study were: the size of citrus trees (small & large), angles of beaters of the canopy shaker (5, 20, and 35 degrees), and the canopy shaker frequencies (200, 250, and 300 cpm). The accelerometers data (the coordinates of x, y, and z-axis) were recorded in text file by using the acquiescent LabVIEW VI software, as represented in Figures 2-24 and 2-25. In addition, the fruit detachment forces FDF (FR) were calculated depending on the accelerometers sense (3-axial acceleration values as recorded in an observable text file) and some standard constants (e.g., accelerometer sensitivity, g value, and the fruit & limbs weight that were selected randomly).

In general, this study has proposed that required forces (maximum force), which are applied for the detachment of Hamlin and Valencia fruit during the harvester operations were 27.20 N and 22.01 N, respectively. In general, Hamlin fruit required less average force than the Valencia fruit. Additionally, the maximum forces for fruit detachment, depending on fruit location, were recorded as 24.49 N on the tree surface and 23.07 N for inside fruit. Depending on the citrus trees sizes, the maximum resultant acceleration values (m/s^2) were found to be 136.01 for the large trees with, the beaters angle and frequency of 5^o and 250 cpm, and 137.95 for small trees with the beaters angle and frequency of 35^o and 300 cpm.

Another study was carried out by Castro-García et al. (2008), on the operation of olive harvesting, which used a trunk shaker approach. The vibration required for olive tree harvesting was measured using 3 tri-axial accelerometers located on various branches and one tri-axial accelerometer placed on the tree trunk (Figure 2-26). The tri-axial accelerometers used were model PCB 356A02, which had sensitivity up to ±10 (mV/g), amplitude range ± 500 g, a

frequency range 0.5 to 6000 Hz, supply current range from 2 to 20 mA, and a weight of 10.5 g. Also, the specific frequencies applied were in the range of 0 to 256 Hz. The maximum excitation frequency was recorded as 71.5 Hz for large trees and 72.4 Hz for small trees.

In addition, vibrations, which were established by a grape harvester with ground speed of 2.8 km/hr, were estimated for the application of various beating frequencies of 380, 400, 420, 440, and 460 (beats/min) to the vineyard. The plant oscillation was determined by three vibration sensors (tri-axial accelerometers). Two accelerometers were posted vertically on some of the grape boughs at different distances (10 and 20 cm from the wire accelerometer on top), while the third accelerometer was placed on top of the trellis wire. The tri-axial accelerometer specifications were a sensitivity of 0.316 (pC/ms^2), frequency range 0.1 to 16500 Hz, and amplitude in range of ±50,000 (m/s^2) with 2.4 g in weight. Furthermore, the vibration sensors had been attached to an amplifier and digital recorder. The vibration measurements were analyzed using LabVIEW 8.0 software. From the results of the operational variables of this experiment, it was found that adequate results were achieved by applying the beating frequency 440 (beat/min) (Pezzi and Caprara, 2009).

Figure 2-1. A pair of OXBO continuous fruit canopy shakers with fruit conveyers. [Adapted from Futch and Roka, 2005]

Figure 2-2. A pair of KORVAN continuous fruit canopy shakers with fruit conveyers. [Adapted from Futch and Roka, 2005]

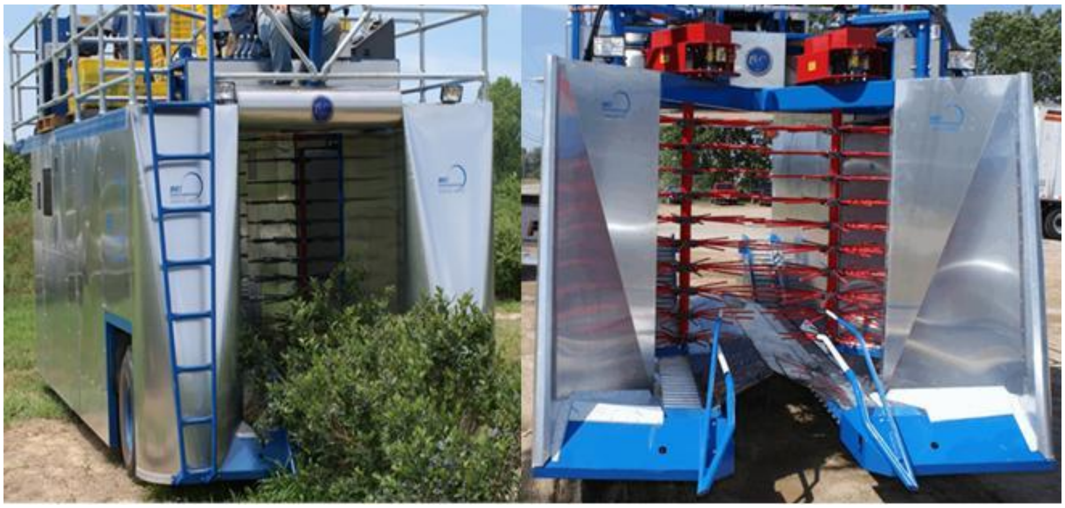

Figure 2-3. Self-propelled BEI harvesters for blueberries fruit. [Adapted from BEI International, LLC, 2010]

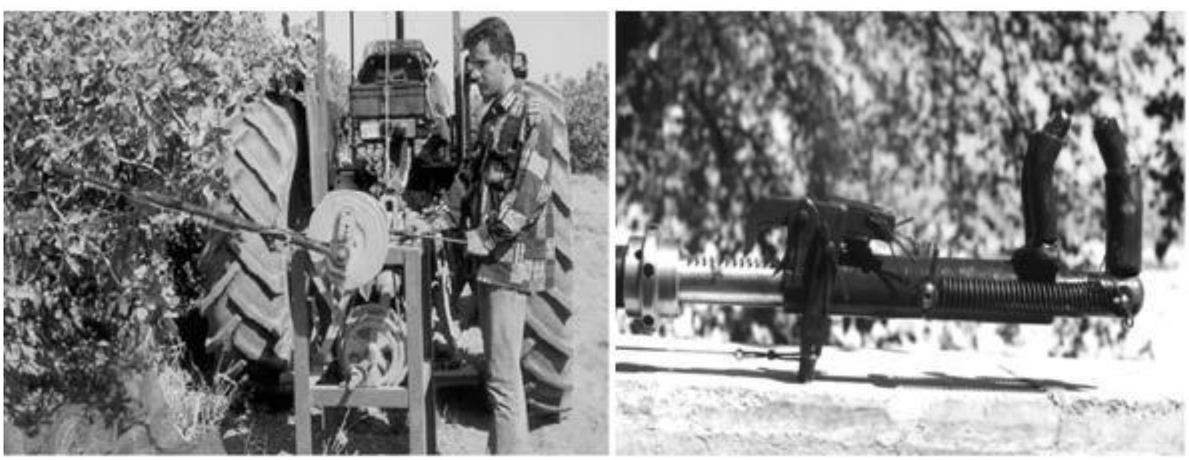

Figure 2-4. An adjustable long beam shaker and its fingers mounted on an agricultural tractor. [Adapted from Loghavi and Mohseni, 2006]

Figure 2-5. A pair of apple harvester machines. [Adapted from Peterson and Wolford, 2003]

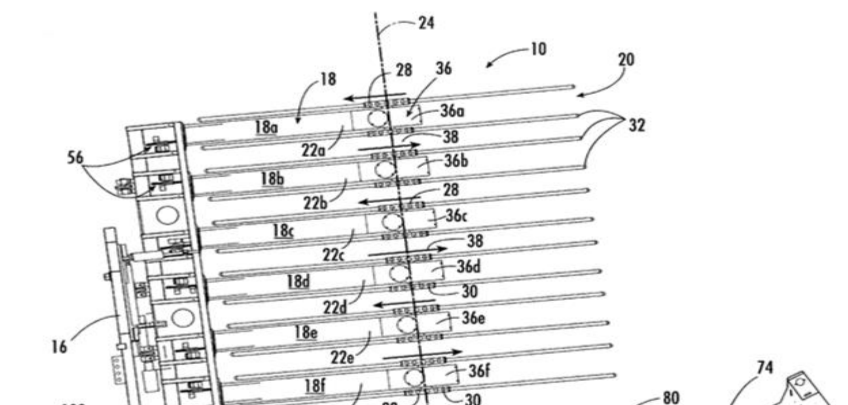

Figure 2-6. Sketch of a canopy shaker. [Adapted from Visser, 2001]

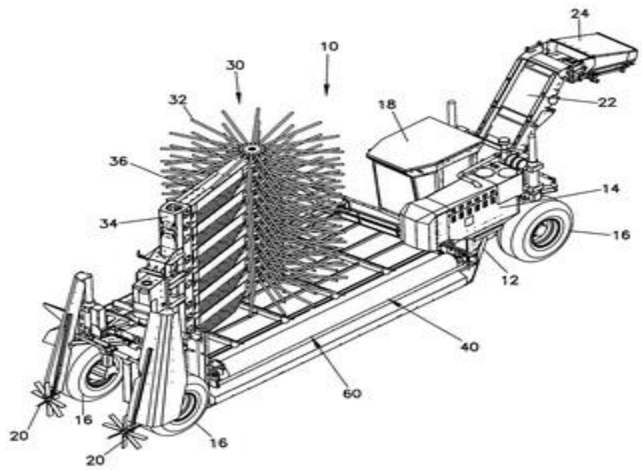

Figure 2-7. Sketch of a citrus harvester machine with fruit conveyer. [Adapted from Schloesser, 2005]

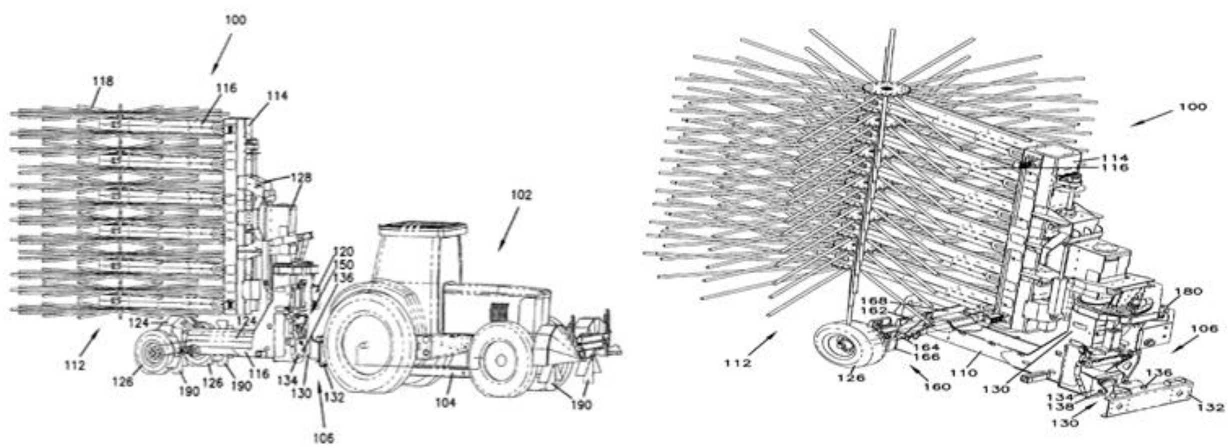

Figure 2-8. Schematic of dragged citrus canopy shaker. [Adapted from Briesemeister et al., 2008]

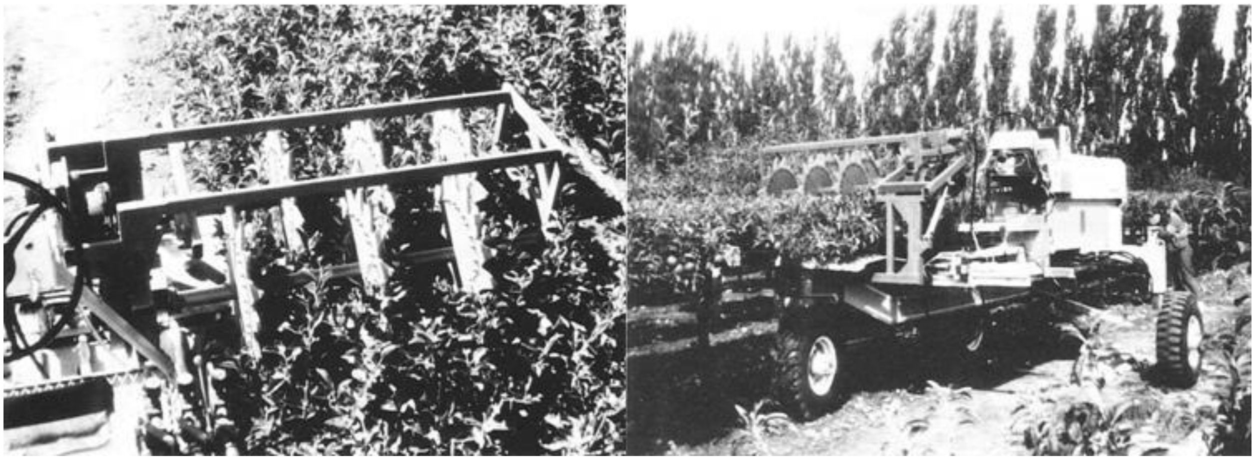

Figure 2-9. Self-propelled apple harvester with horizontal canopy shakers. [Adapted from Láng, 1989]

Figure 2-10. A citrus canopy air shaker towed by a tractor. [Adapted from Coppock and Donhaiser, 1981]

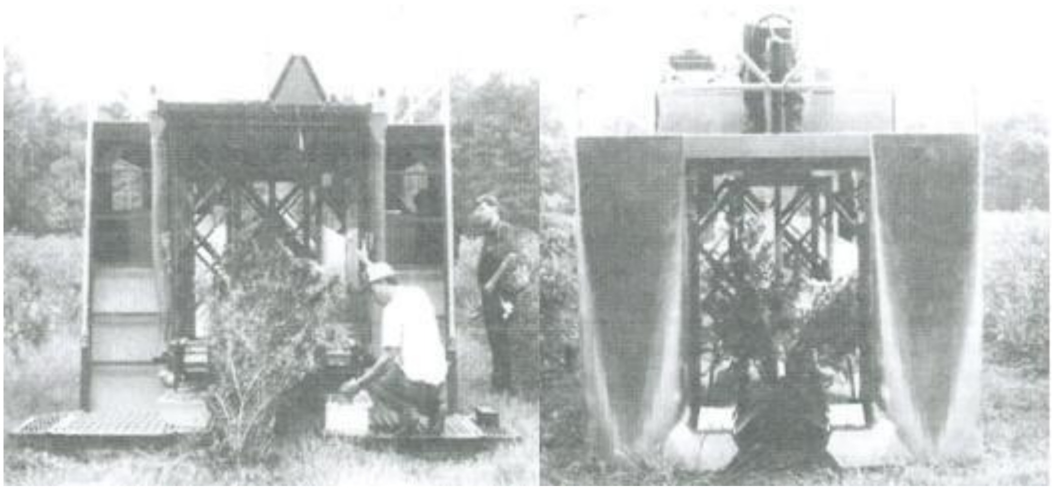

Figure 2-11. Blueberry harvester machine. [Adapted from Peterson et al., 1997]

Figure 2-12. Thornless blackberry harvester machine. [Adapted from Peterson and Takeda, 2003]

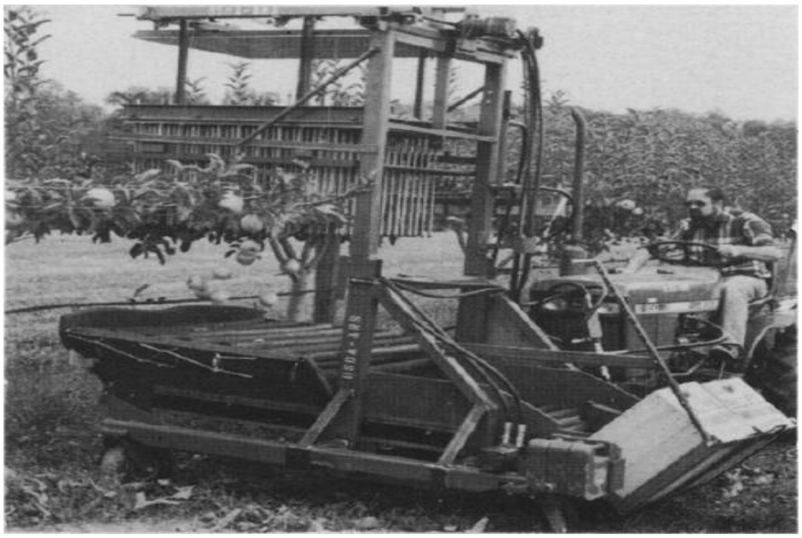

Figure 2-13. An apple harvester for small tree canopies with catch frame. [Adapted from Peterson and Miller, 1989]

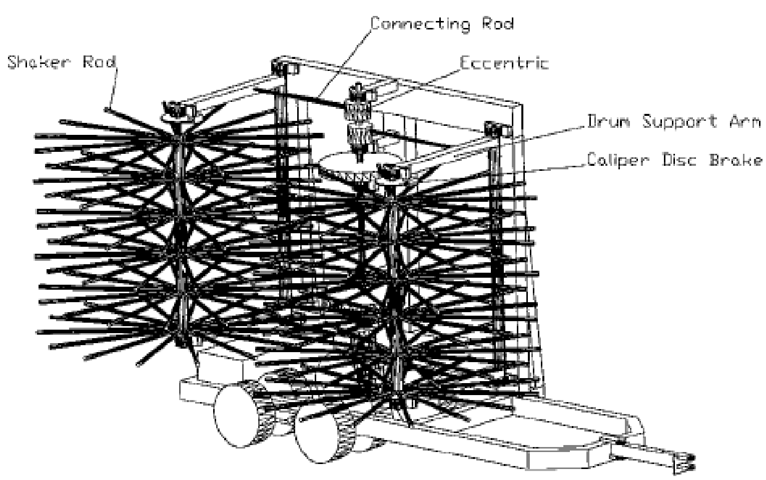

Figure 2-14. Sketch of a continuous pair spokes-drums canopy shaker dragged by a tractor. [Adapted from Peterson, 1998]

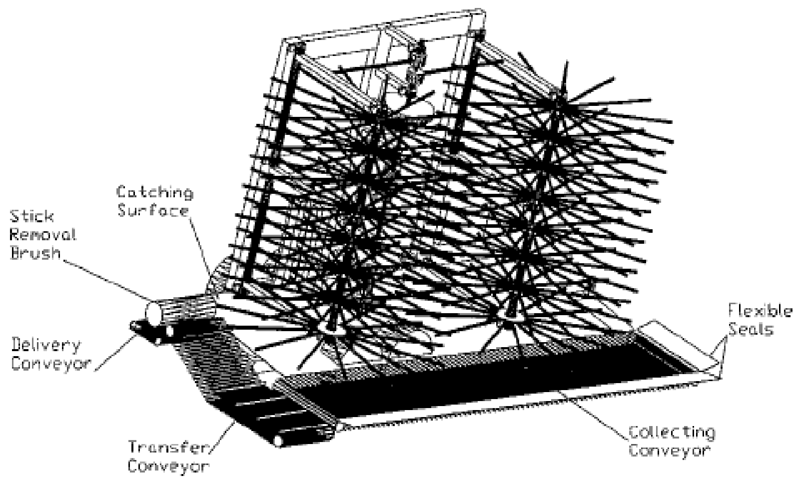

Figure 2-15. Sketch of a continuous pair spokes-drums canopy shaker with oranges fruit conveyer. [Adapted from Peterson, 1998]

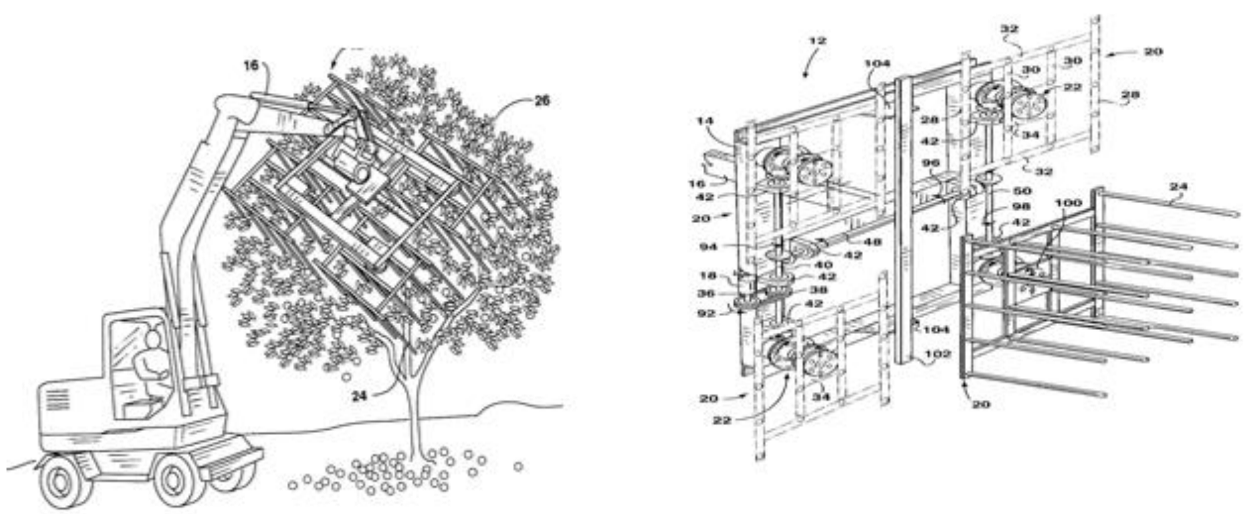

Figure 2-16. A citrus fruit canopy shaker. [Adapted from Hosking, 2002]

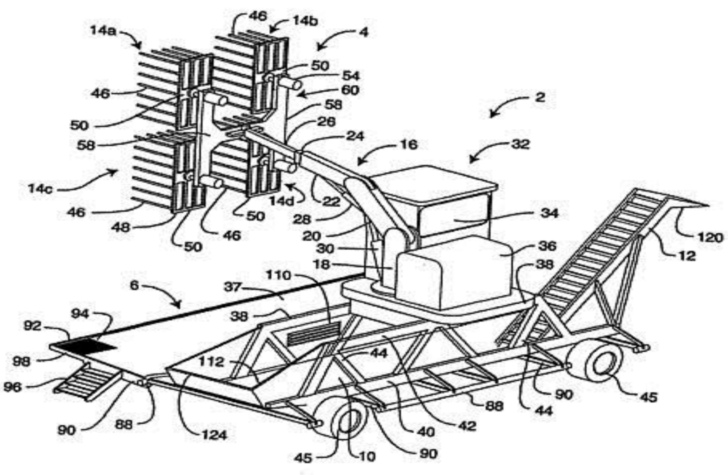

Figure 2-17. Fruit harvester machine. [Adapted from Daniels, 1999]

Figure 2-18. Citrus picking system by using a robotic arm. [Adapted from Hannan and Burks, 2004]

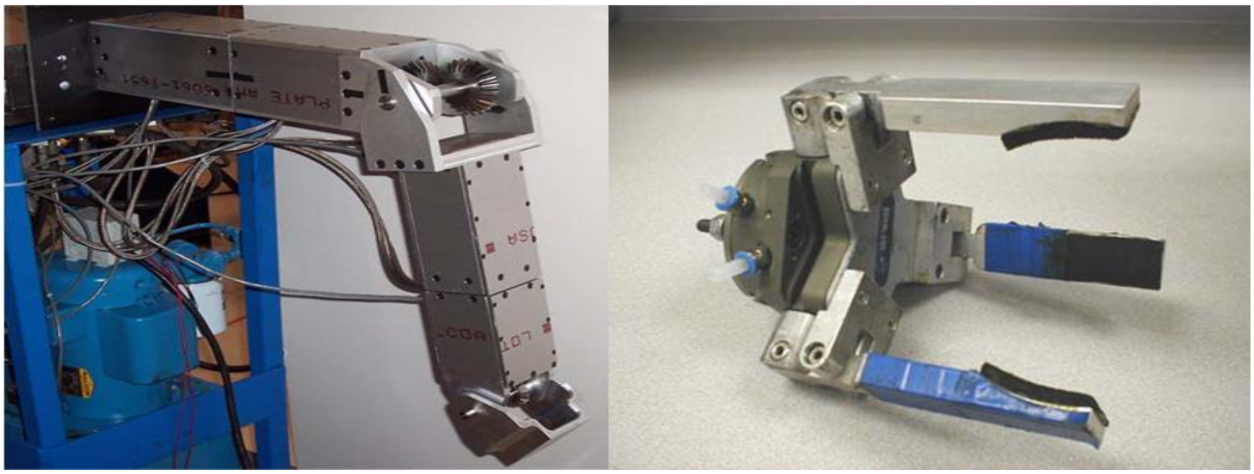

Figure 2-19. Robotic arm modules with end effectors. [Adapted from Sivaraman, 2006]

Figure 2-20. A trunk shaker system. [Adapted from Futch et al., 2005]

Figure 2-21. A canopy shaker unit drawn by an agricultural tractor. [Adapted from Futch et al., 2005]

Figure 2-22. A pair of citrus canopy shakers and two catch systems. [Adapted from Futch et al., 2005]

Figure 2-23. Three-ways to attach the acceleration units throughout the experiment process. [Adapted from Udumala Savary, 2009]

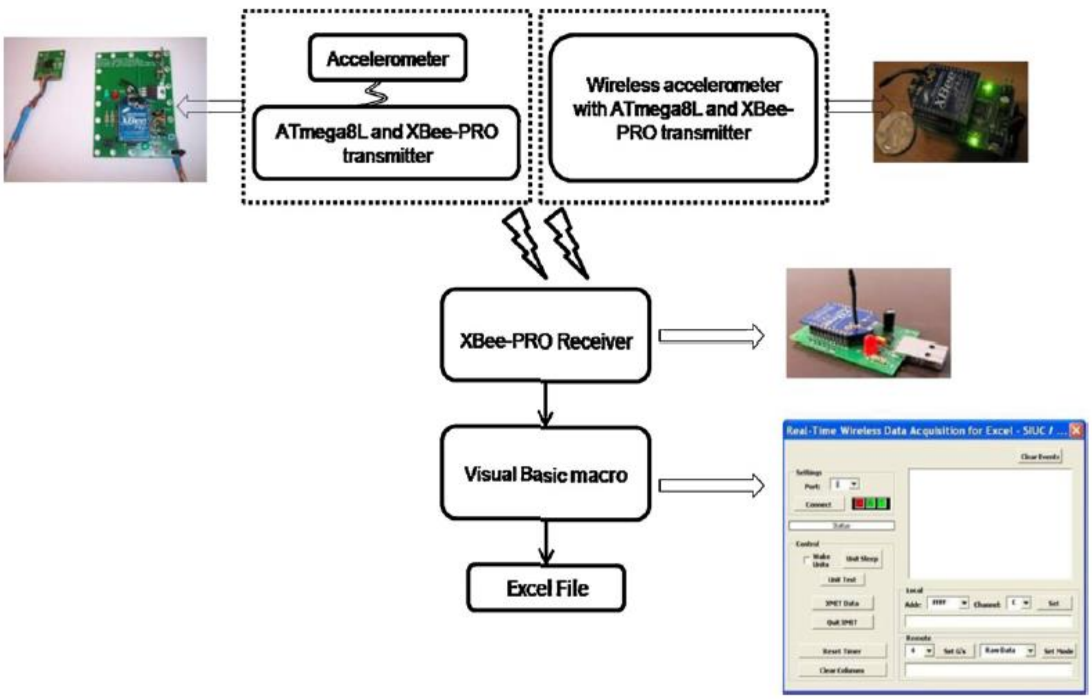

Figure 2-24. Diagram of the acceleration sensors and data collection procedure. [Adapted from Udumala Savary et al., 2011]

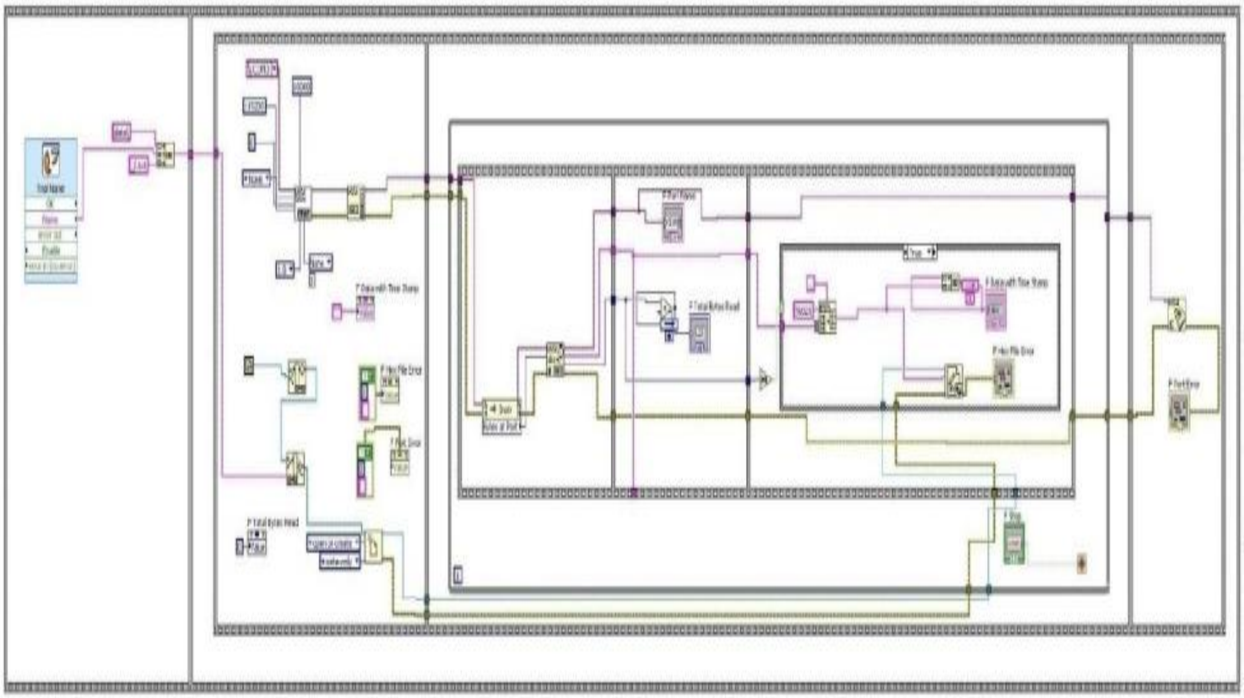

Figure 2-25. LabVIEW block diagram of the data acquisition. [Adapted from Udumala Savary, 2009]

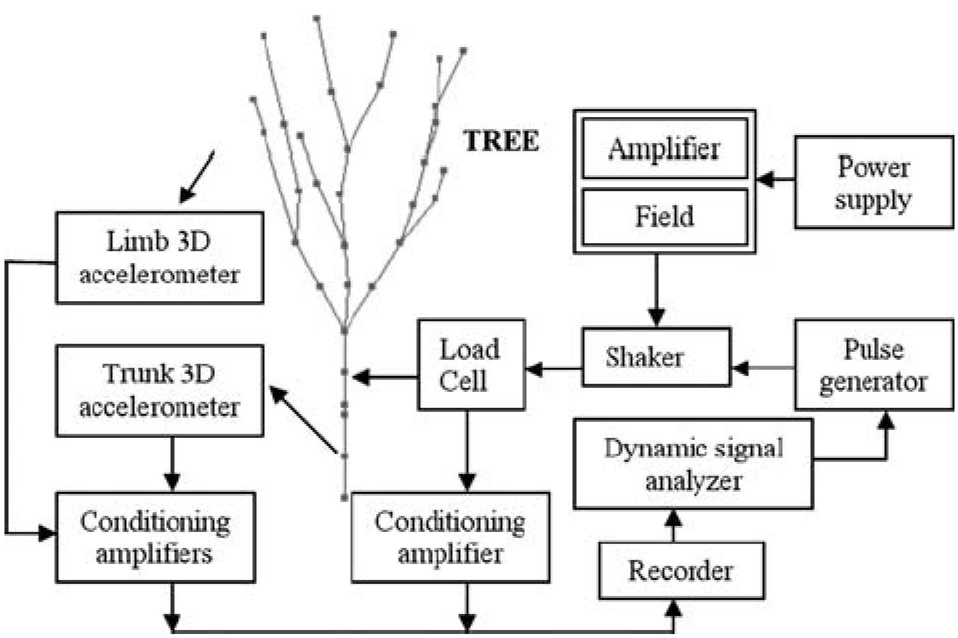

Figure 2-26. Diagram of the acceleration sensors positions, and procedures of the instrumentation experiments. [Adapted from Castro-García et al., 2008]

CHAPTER 3
MATERIALS AND METHODS

Assembly Design Procedures of the Citrus Canopy Shaker (Theoretical)

The dissertation research concept is to design and develop a novel, self-propelled, over the top canopy-shaking machine, which is specialized for harvesting of semi-dwarf citrus trees, where two identical fruit shaker units will surround the canopy of the citrus tree. Initially, the shaker machine was modeled using the SolidWorks program to ensure that the machine parts worked together as expected. Figure 3-1 shows the SolidWorks model.

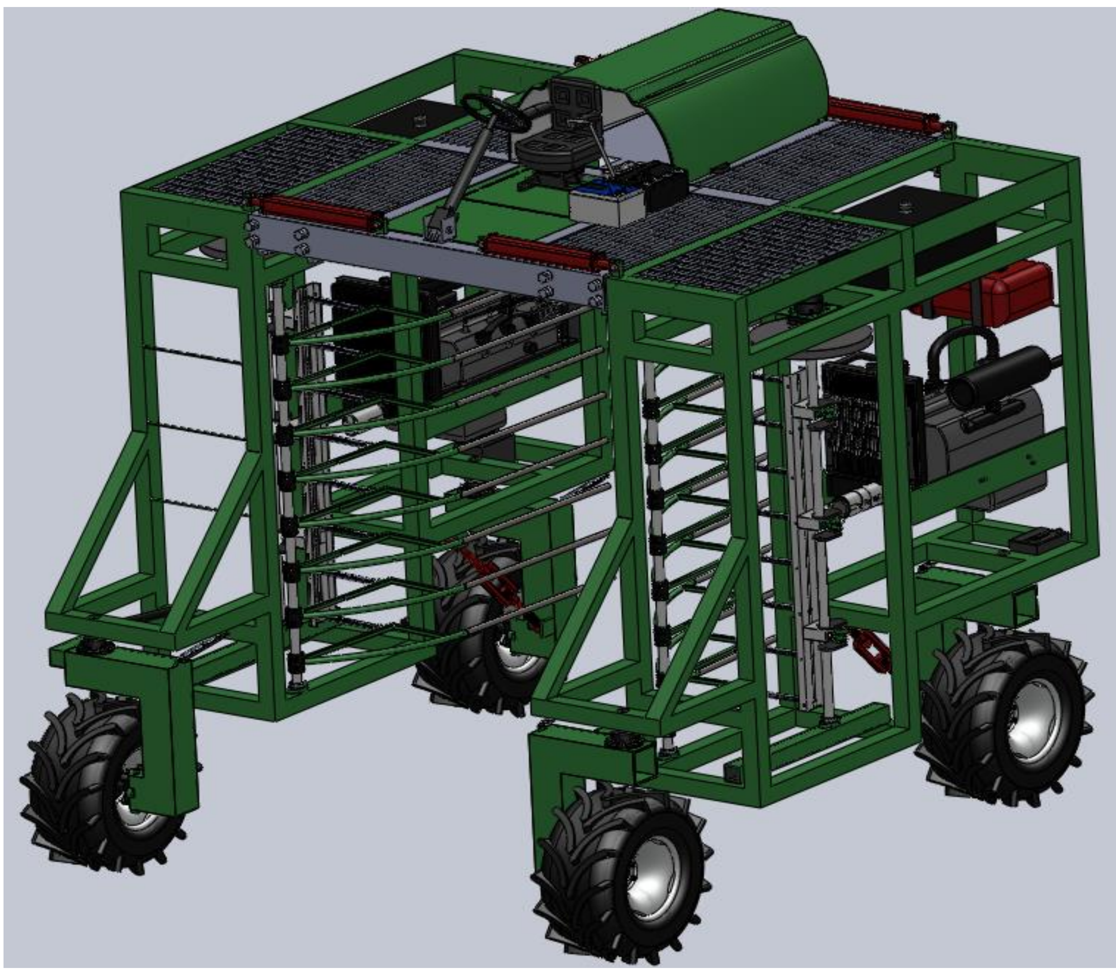

Figure 3-1. A representative self-propelled citrus tree canopy shaker (preliminary design).

The essential purpose of the design process is to analyze how the canopy shakers should be designed so that shakers would deliver suitable fruit removal forces to detach fruit. The fundamental mechanical parts of the canopy shaker were the chassis frame, shaker modules, hydraulics, wheels and motors, steering system, and two engines (18 and 33 Hp). Initially, there were 14 shaking beaters with 14 reciprocating rods (movable turn buckles that extended horizontally), while in the final design, the number of the shaking beaters increased to 26 beaters. A vertical shaft supported the beaters (beaters-holder shafts), while a rotator crank-shaft with a solid flywheel caused the beaters to oscillate, as depicted in previous figure.

Design analysis will determine the required diameters of the shaking beaters, the two vertical shafts, and the horizontal interchanging rods, by first assuming the horizontal load that could be applied at the beaters ends to obtain the suitable limb displacement. The following procedures would be employed to determine the required diameters of the mechanical parts for the new citrus harvester design:

1- Drawing the proper apparatus loads, shears, and bending moment diagrams to determine the maximum and minimum bending moment.

2- Identifying the material properties such as; ultimate strength value, and yield strength.

3- Specifying the factors that will affect the endurance strength.

4- Selecting the stress concentration and design factors.

In essence, the following equations will be utilized to compute the section modulus *S* value. Then, using the section modulus, the desired shaft diameters will be determined (Mott, 2004).

$$S_n' = (C_m)(C_{st})(C_R)(C_s)(S_n) \tag{3-1}$$

$$S = N\left[\frac{M_m}{S_u} + \frac{K_t\,M_a}{S_n'}\right] \tag{3-2}$$

$$D = \sqrt[3]{\frac{32\,S}{\pi}} \tag{3-3}$$

$$A_c = \frac{N}{2}\left[\frac{F_m}{S_{sy}} + \frac{F_a}{S_{sn}'}\right] \tag{3-4}$$

$$D = \sqrt{\frac{4A_c}{\pi}} \tag{3-5}$$

$$D = \left[\frac{32N}{\pi}\sqrt{\left[\left[\frac{K_t M}{S_n'}\right]^2 + \frac{3}{4}\left[\frac{T}{S_y}\right]^2\right]}\right]^{1/3} \tag{3-6}$$

Where, S_n' is the actual endurance strength (psi), C_m is the material factor, C_{st} is the type of stress factor, C_R is the reliability factor, C_s is the size factor, S_n is the endurance strength (psi), S is the section modulus (inch^3), N is the design factor, S_u is the tensile strength (psi), S_y is the yield strength (psi), M_m is the mean bending moment (lb-in), M_a is the alternative bending moment (lb-in), K_t is the stress concentration factor, A_c is the area of the cross-section of the materials used (inch^2), D is the diameter of the materials used (inch), F_m is the mean force (lb), F_a is the alternative force (lb), S_{sy} is the yield strength in shear under actual conditions (psi), S_{sn}' is the endurance strength in shear under actual conditions (psi), π is a constant number, S_y is the yield strength (psi), M is the bending moment (lb-in), and T is the shaft torque (lb-in). Subsequently, the machine design procedures will be handled in the order prescribed.

The Raised Horizontal Beaters Design

The shaker's design process will determine the proper diameter of the beaters of the canopy shaker machine under the shaking load. For the beater diameter estimation, field force measurements were taken by of diverse limb deflections as shown in Table 3-1 and Figure 3-2. The calculations of table 3-1 values are documented in the equations referenced in 3-22 to 3-23 later in this chapter. The maximum load of 50 lb_f (222.41 N), found in Table 3-1, should be enough functional load to deflect the tree branches and their fruits during citrus harvesting to detach the fruit from the tree. Figure 3-3 shows the basic loading design of the horizontal beater (56 inches arc length weighing 20 lb). The beater is shaped like a fuel pump dispenser nozzle. The initial design was composed of steel, while the final design had a composite construction, with steel components at the crank shaft and PVC pipe at the free end. A small metal sleeve (0.5″ at one end and 0.25″ at the other end, and length 4.50 inches) was pushed into the internal holes of the metal pipe and the PVC pipe of the shaking beater (3 inches of the metal sleeve pushed into the PVC pipe and 1.50 inches pushed into the metal pipe) to join them together. This innovative new beater design reduced the gross beater weight from 20 lb to 15 lb with 56 inches arc length, and provides an efficient oscillation for the shakers. Also, this beater design (composed of rounded metal pipes and PVC pipes) would minimize the likelihood of tree canopy damage due to branch and beater collisions.

The beater load diagram shows the bending moment that occurred at the end of the beaters on the vertical shaft. The maximum bending moment is M_{max} = 1,600 lb-in, and the minimum bending moment is M_{min} = -800 lb-in. Therefore, for the beater design analysis, the beater material is specified as AISI 1050 cold-drawn steel that has a yield strength of S_y= 84 ksi and an ultimate strength of S_u= 100 ksi. Those values will be used for all materials of this design.

Then, to complete the beaters design analysis, the equations 3-1, 3-2, and 3-3 will be utilized (Mott, 2004).

From the value of bending moment, the maximum bending moment is M_{max}= 1,600 lb-in and the minimum bending moment is M_{min} = -800 lb-in. Thus, the mean bending moment is 400 lb-in ($M_m = (M_{max} + M_{min})/2$), and alternating bending moment is 1200 lb-in ($M_a = (M_{max} - M_{min})/2$). Because the beaters will be of uniform diameter along the beater length, the stress concentration factor is set at K_t = 1.0. Because this design has a somewhat constant beating rhythm, the design factor for equation 3-2 was selected as N=2.0.

The endurance strength of the material under actual working conditions can be determined by using equation 3-2. The endurance strength is assumed to be S_n = 38 ksi for the beaters having S_u= 100 ksi. For the wrought steel, the material factor is expected to be C_m = 1.0 and the stress-type factor of C_{st} = 1.0 for the repeated bending stress. The reliability factor is chosen as C_R = 0.81 to achieve a reliability of 0.99. Because the rod diameter was not determined yet, the value of size factor is expected as C_s= 0.95 (Mott, 2004). By using these values, equation 3-1 was used to determine the required value of endurance strength S_n'= 29,241 psi. Furthermore, equation 3-2 calculated the required section modulus S = 0.09 inch^3. By applying the section modulus value to the equation 3-3, the rod diameter came out to be 0.971 inch. Thus, the harvester beater diameter was chosen to be 1 inch.

Table 3-1. The field measurements of the pulled forces achieved by effect of different manual orange limb deflections.

No	$Di._f$ in	A_c in^2	I in^4	L_{bf} in	Dis. 3.94 (in) F lb_f	E ksi	Dis. 5.91 (in) F lb_f	E ksi	Dis.7.87 (in) F lb_f	E ksi	Dis. 9.84 (in) F lb_f	E ksi
1	0.58	0.26	0.005	33.5	5	2.52	8	6.04	10	10.07	12	15.10
2	0.61	0.3	0.007	23.5	20	6.26	30	14.08	42	26.28	50	39.11
3	0.69	0.38	0.011	32.5	4	1.35	7	3.56	9	6.09	11	9.31
4	0.57	0.25	0.005	43	2	1.35	4	4.04	5	6.73	6	10.09
5	0.54	0.23	0.004	70	1	1.19	2	3.56	3	7.12	4	11.87
6	0.41	0.13	0.001	34	7	7.27	11	17.14	14	29.08	16	41.55
7	0.54	0.23	0.004	54.5	3	2.81	4	5.63	6	11.26	8	18.77
8	0.78	0.48	0.018	54	2	8.87	3	1.99	5	4.44	6	6.65
9	0.85	0.56	0.025	39.5	14	3.87	20	8.29	25	13.83	29	20.05
10	0.72	0.41	0.013	41.5	6	2.41	9	5.42	12	9.63	15	15.04
11	0.68	0.37	0.011	48	6	3.08	10	7.71	12	12.34	15	19.28
12	0.44	0.15	0.002	34.5	3	2.65	5	6.64	7	12.39	9	19.91
13	0.67	0.35	0.010	43.5	10	4.83	15	10.86	20	19.31	24	28.96
14	0.84	0.56	0.025	55	18	7.01	25	14.59	33	25.69	40	38.92
15	0.58	0.26	0.005	31	23	10.73	32	22.40	41	38.26	45	52.49
16	0.58	0.26	0.005	45	3	2.03	5	5.07	7	9.47	9	15.21
17	0.62	0.31	0.007	60.5	3	2.34	5	5.84	7	10.90	9	17.52
18	0.38	0.11	0.001	52.5	2	3.66	3	8.24	5	18.31	7	32.05
19	0.77	0.47	0.018	41.5	15	5.21	21	10.95	30	20.85	38	33.02
20	0.6	0.28	0.006	53	11	8.24	15	16.85	20	29.96	25	46.81
Ave.	0.62	0.32	0.009	44.5	8	3.98	12	8.95	16	16.10	19	24.59
S.D.	0.13	0.13	0.007	11.5	7	2.69	9	5.48	12	9.45	14	13.52

Figure 3-2. Field measurement of the citrus fruit detachment force. [Photo courtesy of Naji Al-Dosary]

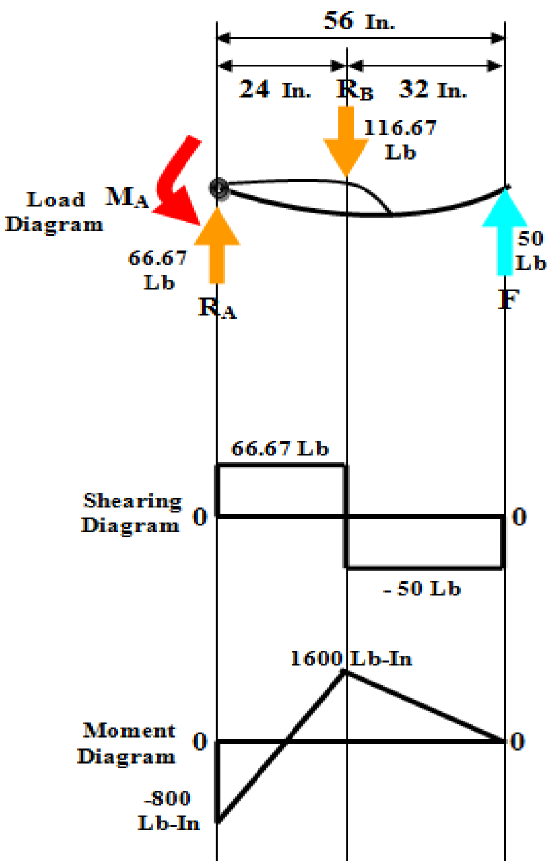

Figure 3-3. Basic design of the horizontal beater and its load.

Vertical Beaters-Pivot Shaft Design

The vertical beaters-pivot shaft is connected to the end of the shaking beaters to hold them in vertical position, and allow them to oscillate to the movement from the movable crank-shaft. The shaft is mounted to the harvester body by the two flange bearings at the two ends of the beaters-shaft. Bending moment will occur due to the beater reaction forces. Since the shaft is free to rotate, there will be no torsion loading. The beaters are mounted vertically on each beaters-pivot shaft at equal spaces, 8 inches apart. The Figure 3-4 shows the basic design of the vertical beaters-pivot shaft and its horizontal loads. The maximum bending moment is M_{max}= 5224.84 lb-in and the minimum bending moment is M_{min} = 0 lb-in. Thus, the mean bending moment is M_m = 2612.42 lb.in ((M_{max} + M_{min})/2) and the alternating bending moment value is M_a = 2612.42 lb.in ((M_{max} - M_{min})/2). Therefore, for the beaters-pivot shaft design analysis, the shaft material is specified as AISI 1050 cold-drawn steel that has a yield strength of S_y= 84 ksi and an ultimate strength of S_u= 100 ksi. The endurance strength is assumed to be S_n = 38 ksi for the beaters. In addition, because the shaft's diameter was not determined yet, the value of size factor is selected as C_s= 0.85. The design factor for equation 3-2 was selected as *N*=2.50, since this design has a somewhat uncertain dynamic load from the environment (Mott, 2004).

The same techniques and materials that were considered to determine the beater's diameter were considered for the beaters-pivot shaft diameter calculation. Thus, the required value of endurance strength is S'_n= 26,163 psi. Furthermore, the required section modulus value is S = 0.314 inch^3. By applying the section modulus value to equation 3-3, the shaft diameter came out to be 1.471 inches. However, for more operational safety, the shaft diameter is taken as 1.50 inches. Depending on the cyclical rotation of the beaters-pivot shaft (15 degrees), the canopy shakers displacement (beaters penetration), acceleration, and beaters frequency will be determined.

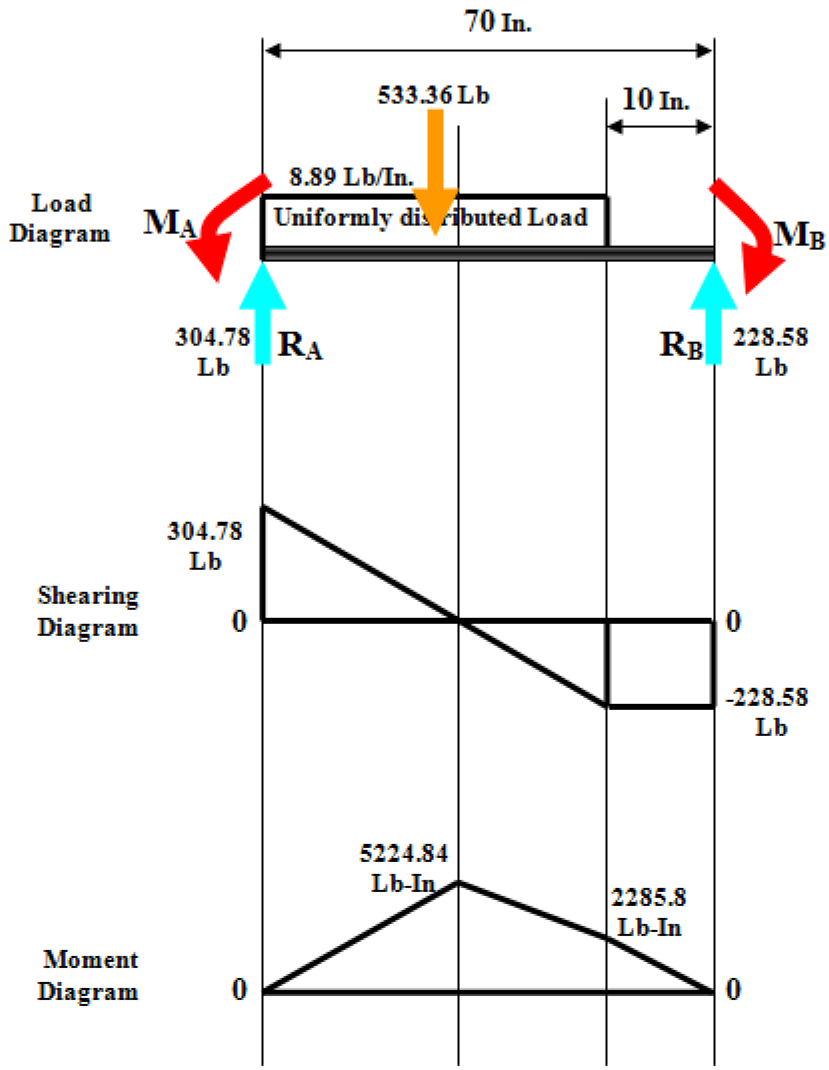

Figure 3-4. Basic design of the vertical beaters-pivot shaft and its load.

Vertical Crank-Shaft Design

The crank-shaft is connected to an aluminum channel by three bearings, which in turn is connected to the beaters by turn buckles. The crank-shaft is mounted on the harvester body by two flange bearings that are pushed onto the two shaft ends. Therefore, the bending moment and torsion will occur on the crank-shaft. Figure 3-5 depicts the basic design of the vertical beaters-shaft and its horizontal loads. From the value of the bending moment, the maximum bending moment is M_{max}= 8729.06 lb-in and the minimum bending moment is M_{min} = 0 lb-in. Thus, the

mean and alternating bending moments are equal. Thus, the mean bending moment M_m = 4364.53 lb.in is likewise the alternating bending moment M_a = 4364.53 lb.in. Therefore, for the beaters-shaft design analysis, the shaft material is specified as AISI 1050 cold-drawn steel having a yield strength of S_y= 84 ksi and an ultimate strength of S_u= 100,000 psi. The endurance strength is assumed to be S_n = 38,000 psi. Also, this shaft is designed with the combination of torsion, shear, and bending moments. So, the calculated maximum torque was T= 2,800.0 lb-in, and 8729.06 lb-in of the moment value will be used to determine the shaft diameter. In addition, because the diameter of the shaft was not determined yet, value of the size factor is selected as C_s= 0.85. Also, the value of the stress concentration factor is selected as K_t = 1.0, and the design factor for equation 3-6 was selected as N=2.0. As a result, the shaft design has a high confidence with a static load (Mott, 2004).

Likewise, the same practices and materials that were applied to determine the beaters-pivot shaft and its associated beaters diameter would be used for the crank-shaft diameter calculation. Consequently, the required value of the endurance strength is S_n'= 26,163 psi. Furthermore, the required section modulus value is S = 0.420 $inch^3$. By applying the shaft torque and moment values to equation 3-6, the crank-shaft diameter comes out to be 1.896 inches.

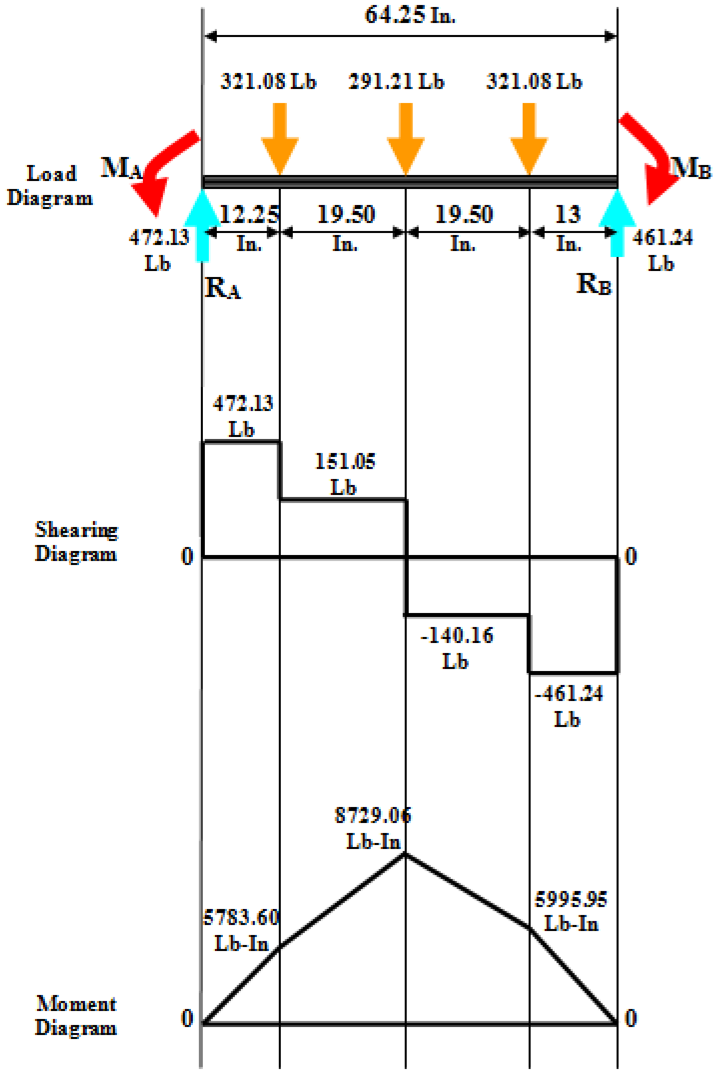

Figure 3-5. Basic design of the vertical crank-shaft and its load.

Horizontal Push Rods (Interchanging Turn Buckles) Design

In general, for each canopy shaker unit, the beaters-pivot shaft and the crank-shaft are attached together by seven horizontal rods (turn buckles). Figure 3-6 shows the basic design of the horizontal push turn buckle with its horizontal loads, where it is acted upon by two identical forces in opposite directions (-116.67 lb compressive load and 116.67 lb pull load). Therefore, in the push rod (turn buckle) design analysis, the shaft material is assumed to be as AISI 1020 cold-drawn steel that has a yield strength of S_y= 51 ksi and an ultimate strength of S_u= 61,000 psi. The

endurance strength is assumed to be S_n = 23,000 psi for the rod with an ultimate strength S_u= 61 ksi. Thus, maximum force (F_{max}) is 116.67 lb and the minimum force (F_{min}) will be -116.67 lb. For the specified steel of this push rod, the material factor is expected as C_m = 1.0 and the stress-type factor is C_{st} = 0.80 for the axial tension. The reliability factor is chosen as C_R = 0.81 to achieve a reliability of 0.99. Because the diameter of the reciprocating rod was not determined yet, the value of size factor was selected as C_s= 0.90. Hence, the design factor was selected as *N*= 4.0 due to somewhat uncertain dynamic loads for the machine components or environment (Mott, 2004). Thus, the mean force is F_m = 0 lb ($F_m = (F_{max} + F_{min})/2$) and the alternating force is F_a = 116.67 lb ($F_a = (F_{max} - F_{min})/2$). By using the values of the estimated forces, the equation 3-1 exercised for required value of endurance strength is S'_n = 13,413.6 psi then the endurance strength value in shear under actual conditions is S'_{sn} = 7,739.65 psi (S'_{sn}= 0.577S'_n) and S_{sy}= 29,427 psi (S_{sy}= 0.577 S_y). Furthermore, by applying those values in the equations 3-4 and 3-5, the required push rod area will be presented as A_c = 0.03 inch^2. Thus, push rod diameter is 0.1954 inch (1/4 inch). Preferably, for more operational safety, the diameter of the reciprocating rod is assumed to be 1/2 inch in circular shape.

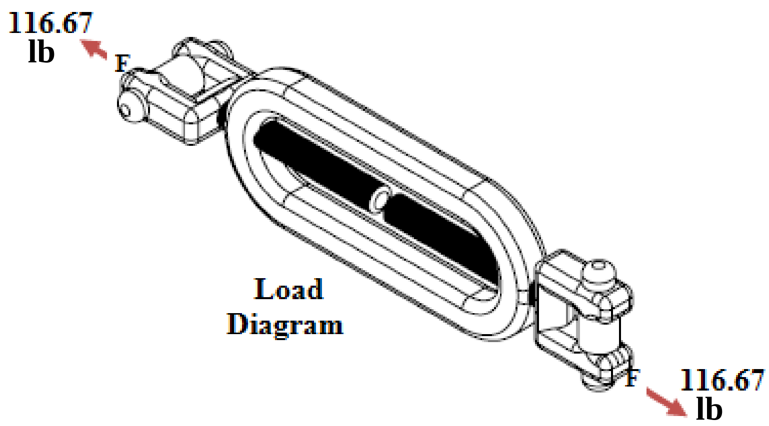

Figure 3-6. Basic design of the horizontal push rod and its loads (reciprocating turn buckle).

Vertical Connecting Beam (Interchanging Beam) Design

Figure 3-7 shows the basic analysis of the vertical connecting beam design (62 inches in length) and its loads. The vertical connection beam (U shape aluminum channel) is connected to seven identical horizontal rods (turn buckles) and the shaker crank-shaft by three short aluminum rectangular solid bars (5×4×2 inches), and their connecting radial bearings, using two bolts on each side of the short aluminum bar. The maximum bending moment found as M_{max} = 236.6 lb-in and the minimum bending moment was M_{min} = -1030.90 lb-in. Therefore, for the beam design analysis, the beam material is specified as 6061-T6 aluminum beam in channel shape that has a tensile strength of S_u= 45 ksi and yield strength of S_y= 40 ksi. Those values will be used for all materials of this beam design. Then, for completing the design analysis, equations 3-1 and 3-2 will be utilized (Mott, 2004). So, from the values of the bending moments, the mean bending moment value ($M_m = (M_{max} + M_{min})/2$) is M_m = -397.15 lb-in, and alternating bending moment value ($M_a = (M_{max} - M_{min})/2$) is M_a = 633.75 lb-in. The endurance strength is estimated to be S_n = 20 ksi for the aluminum beam that has an ultimate strength S_u= 45,000 psi. Also, the value of the stress concentration factor is selected as K_t = 1.0, and because of the static loads, the design factor value selected for equation 3-2 produces is N=3.5. For the aluminum alloy, the material factor is expected as C_m = 0.5 and the stress-type factor is C_{st} = 1.0 for the repeated bending stress. The reliability factor is chosen as C_R = 0.75 to achieve a reliability of 0.999 and the value of size factor is estimated to be C_s= 0.90 (Mott, 2004). By using those values, equation 3-1 is exercised for required value of endurance strength S_n'= 6,750 psi. Moreover, equation 3-2 presented that the required section modulus value is S = 0.298 in^3. Consequently, the specified size for this beam is expected to be 3 inches (depth) and 1.75 inches (width) but for more adequate design, aluminum c-shape beam with size 5 inches in depth and 2.25 inches in width is chosen (Mott, 2004).

Finally, the design of the new canopy shaker machine consists of several main assemblies. The first one is the symmetric rigid exoskeleton, second and third are the two main movable parts, the crank-shaft and the beaters-pivot shaft. The fourth effective part is the extended rods (seven horizontal interchanging push turn buckles on each side) with an aluminum channel, which are used to deliver the linear speed from the crank-shaft to the beaters-pivot shaft for each shaker unit. So, the selected member diameters for these essential parts are shown in Table 3-2.

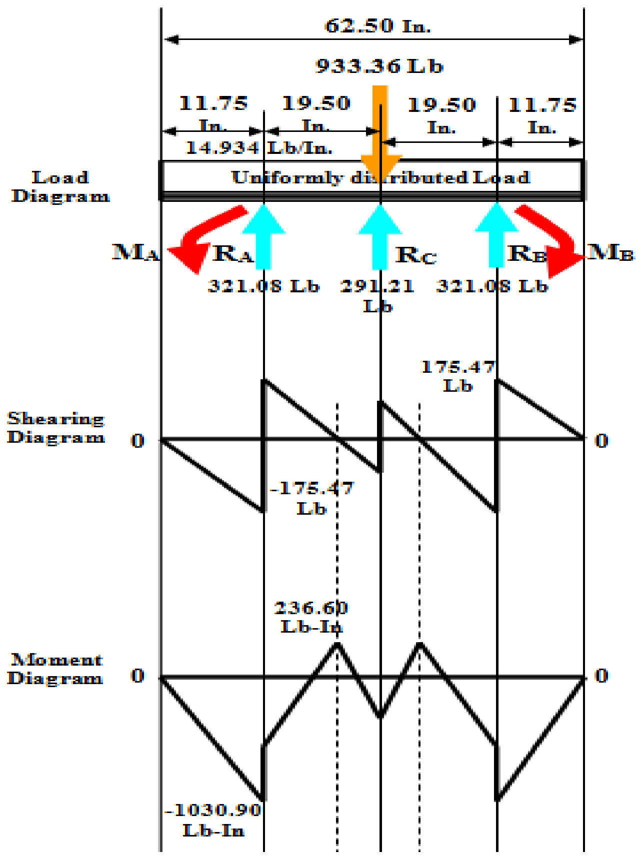

Figure 3-7. Basic design of the vertical connecting beam and its load.

Table 3-2. Most important parts diameters of the representative harvester design (initial design).

Parts	Designed Diameter (in)	Calculated Diameter (in)
Beaters	1 (Hollow Metal) & 0.5 (PVC Pipe)	0.971
Beaters-Pivot Shaft	1.50	1.471
Crank-Shaft	1.50	1.896
Interchanging Rod	0.50	0.195
Connecting Beam	5 (Depth) × 2.25 (Width)	3 (Depth) × 1.75 (Width)

Realistic Design of the Principal Canopy Shaker Machine

The self-propelled citrus canopy shaker is designed specifically for harvesting of fruit from semi-dwarf citrus trees planted in hedgerow. With this canopy shaking system, some important parameters need to be determined through the course of this study to obtain an excellent harvesting operation. These factors can include: dislodgement forces, forward speeds of the harvester, rotational speeds of the shaking beaters, beater stroke length, the numbers of the beaters on the shaking apparatus, and the vibration period. Other factors of interest, which will depend on shaker effectiveness, are the desired harvest efficiency, amount of tree debris, and the limb and bark damage. The canopy shaker assembly shown in Figure 3-8, provides the source of tree canopy excitation necessary to detach the fruit.

The shaker modules are mounted within a welded framework that forms a tunnel around the tree. The frame is composed of rectangular steel tubing segments (size 3×3×0.25 inches, 5×3×0.25 inches, and 6×4×0.25 inches), which are mounted on two pairs of front and rear hydraulically powered wheels with Firestone tires (26×12.00-12). The lateral distance between wheels (side to side) is variable, depending on the extendable hydraulic cylinders on top of the harvester, but should be not less than 69 inches or more than 101 inches in overall width.

Both shakers, which transfer the shaking motion into the tree canopy to dislodge the citrus fruit, have a semi-curved shape (1 inch diameter metal part and 1/2 inch of the PVC part diameter × 56 inches in arc length) which reduces tree injury and increases the interacting surface with the tree along the length of the shaking beaters. After the first test of the shaking machine, the hollow PVC pipes were replaced by flexible solid 1 inch (OD) round PVC grey rods 32 inches long. Testing of the solid PVC rods revealed fatigue can occur when using high shaking frequencies. Initially, two hydraulic motors (model Eaton, Char-Lynn W 162-1146-003 type, displacement of 195 cc/rev, 10 gpm, and pressure 1800 psi) were used to provide the

continuous spinning motion of the two vertical crank-shafts (three crank throws on each shaft). Later, two new hydraulic motors (model Eaton, Char-Lynn 2000 series 104-1009-006 type, with displacement of 6.20 cu.in/rev (101.6 cc/rev), 20 gpm, and pressure 3000 psi) were utilized because the previous hydraulic motors had a limited maximum rotational speed of 200 rpm. Two squads of shaking beaters are extended horizontally on each side of tree, and arranged on two primary beaters-pivot shafts. The number of the beaters per side depends on the height of the citrus trees, and the beaters spacing. The vertical beaters-pivot shaft, which holds each reciprocating beaters squad of seven identical bent beaters, derives its motion from the rotational movement of the crank-shaft that is vertically coupled to its associated hydraulic motor. In order to maintain crank-shaft rotational momentum, a solid steel flywheel (i.e., 127 lb weight, diameter of 19.50 inches, and 1.50 inch in thickness) was mounted on the upper end of each crank-shaft to ensure that the vertical crank-shaft rotates at a constant rotational speed. Each flywheel is coupled to the hydraulic motor shaft and the upper end of each crank-shaft by using an appropriate mechanical shaft coupling.

The tree canopy will be partially surrounded when the pair of harvester shaking beaters forms a "Λ" shape against the tree canopy, and is operated within the adjustable machine tunnel. The tunnel dimensions are initially 69 inches with a variable-width (69-101 inches) × 104 inches in height from the ground × 90 inches in depth. The dimension of the citrus harvester exoskeleton was determined to be 121 inches of the minimum span-width (121 to 153 inches) × 107.50 inches in total height from the ground × 114 inches in machine total length. In addition, the beater assemblies will be extended into the tree canopies when the canopy shaker is being passed through the citrus groves. The range of beaters penetration within the tree canopies is modulated by modifying the length of the short connecting rods (reciprocating turn buckles),

which have a reciprocating movement horizontally between the crank-shaft and the vertical beaters-pivot shaft. Displacement of the shakers stroke is modified by adjusting the turn buckle length. Displacement of the shakers stroke is constant with crank diameters of 6 inches. Also, the shaking speeds (synchronized speeds) of the 14 beaters can be changed by regulating the hydraulic motors speed manually via adjusting the speed of the Mitsubishi engine (maximum engine speed is 3000 rpm) or the two flow control valves which are a part of the John Deere relief valve block. To achieve the full potential engine speed on both engines, each engine throttle can be adjusted by unlocking it, and pulling it from its initial hooking position, as shown in Figure 3-9.

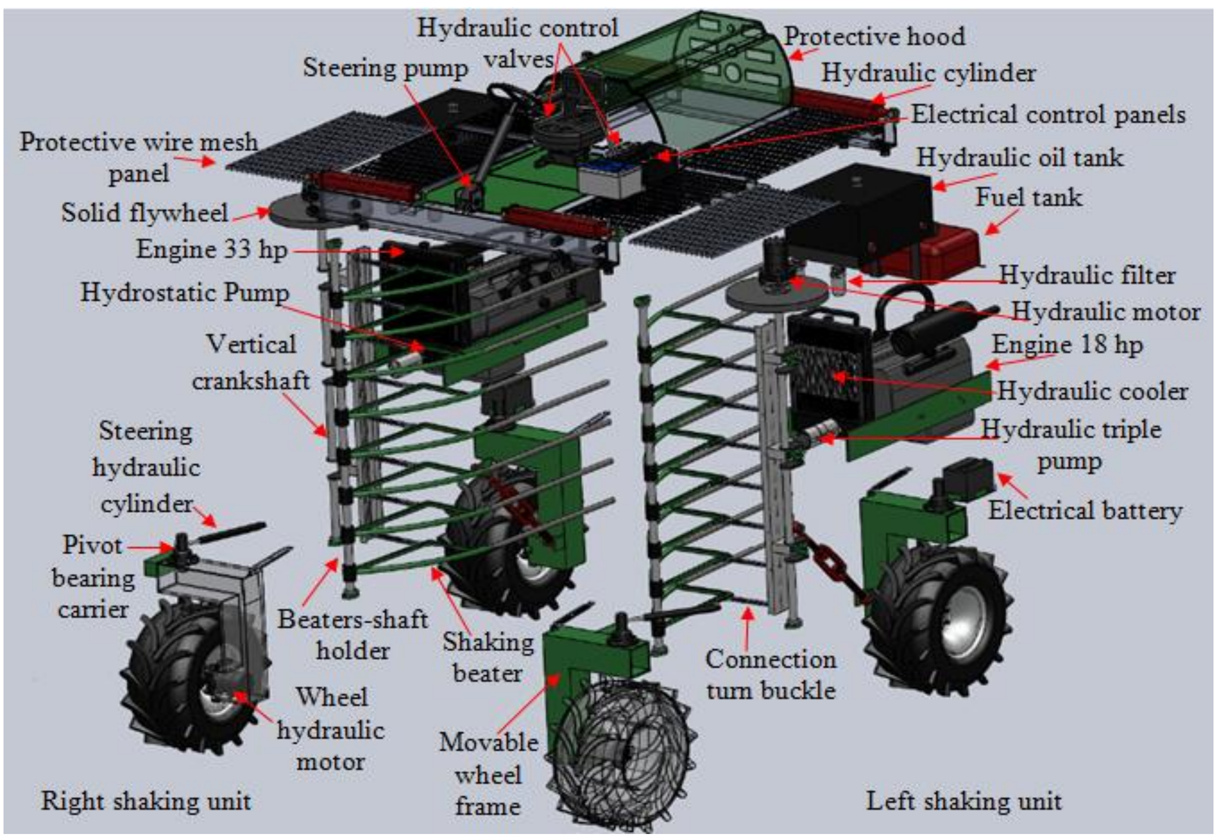

Figure 3-8. Major components of the innovative citrus canopy shaking machine (preliminary design).

Figure 3-9. Two hand engine throttles (cables) of the preliminary citrus canopy shaker design. [Photos courtesy of Naji Al-Dosary]

Overall, the citrus harvester has three major hydraulic operational systems: hydraulic control system for canopy shaker transport speeds, hydraulic control system of the beaters shaking speeds, and hydraulic control system for the width of the internal tunnel of the canopy shaking machine (both right and left side horizontal movement). The hydrostatic transmission system of a John Deere 3225B golf lawn mower by Eaton (model 70119-400 type of a single rotator piston pump with a swash-plate mechanism that can be adjusted manually, 3600 rpm, pressure 4500 psi, and displacement of 23.6 cc/rev (approximate)), is utilized to provide forward/reverse and speed control requirements, and results in suitable field transport speeds. Consequently, an open-center hydraulic directional control valve (prince motor spool valves with a manual control lever-joystick handle), set at the left side of the operator's seat, is used to control all the wheel motors (four identical motors made by Ross). Wheel drive is achieved by four independent wheel motors made by Ross (model ME 103108 CCCB type, low speed and high torque at 399 rpm, displacement of 169 cc/rev, and pressure is 3000 psi) attached to

associated wheel hubs and tires. The rear and front wheels are independent four-wheel drive and synchronized to move simultaneously (forward or reverse travel). Furthermore, hoses, with proper fittings, carry the fluid flow from the hydrostatic pump to the proper motors to provide the rotary motion of the harvester wheels.

In general, the canopy shaking machine will be continuously moving (self-propelled), while the machine is actively harvesting. The propulsion power is provided by a Yanmar diesel engine out of a John Deere 3225B golf lawn mower (Yanmar 3TNE84-EJF with 24.9 kw (33.4 hp), and revolution speed up to 3000 rpm), and a triple gear pump (Sets by Danfoss, part number AMT1951 and model 163C1001 & AD100C) mounted to an Eaton hydrostatic pump. The front pump outlet of the hydraulic triple pump is employed to supply charge flow to the hydrostatic transmission, while the other two outlets of the triple pump are recirculating the hydraulic fluid to the reservoir. The front pump of the Danfoss triple pump supplies hydraulic fluid flow to the four wheel motors, extension or retraction of the double acting hydraulic cylinders, and the steering control valve through the outlet ports of the hydrostatic transmission. The schematic diagram of the hydraulic control system of the self-propelled canopy shaker is shown in Figure 3-10.

Moreover, the shaker motor hydraulic circuit is made up of two identical John Deere 3225B lawn mower pressure relief valves, which send the hydraulic fluid to the hydraulic motor on each shaker (each motor is attached at the top of each flywheel on the crank-shaft of each shakers unit). The shaker brake solenoid valves (On/Off), and the flow control valves in the two J.D. relief valve blocks, are utilized to control the machine’s shakers hydraulic system. A Toro Reelmaster 5300-D golf lawn mower engine (Diesel engine model Mitsubishi type S3L2-002861-1523N with 18 hp engine power (13.4 kw) and maximum revolution speed of 3000

rpm), mounted with a triple pump (by John S. Barnes Corp. 93-1376 & 10294), is utilized to provide power to the shaker fluid system. The three outlet ports of the hydraulic triple pump (front, center, and rear pumps) are combined together and then split 50%-50% to drive the right and left shakers motors. The schematic diagram of the hydraulic control system of the two canopy shaker units is demonstrated in Figure 3-11.

For the internal tunnel width extension, four extendable hydraulic cylinders were mounted on the top of the right and left canopy shaker structure, and were controlled by an open center hydraulic directional control valve (joystick handle) positioned on the right side of the operator’s seat. Extension or retraction of the double acting hydraulic cylinders is performed by activating the hydraulic fluid via the operation of the front pump of the John Deere 3225B triple pump through the hydrostatic pump port, as previously shown in Figure 3-10. For convenience, the two hydraulic control valves are located on the right and left, close to the operator's seat at the front top of the canopy shaker structure, so the operator can easily control and monitor the systems’ operations. Moreover, the two engines with their attached triple pump, fuel tank (6 gallon capacity), and the hydraulic oil reservoir (15 gallon capacity) were located underneath the top of the canopy shaker structure and behind the operator's seat. The flexible hydraulic hoses rated for 3000, 4000, and 4800 psi pressure (quality of two wire braid hose with female swivel fittings), as shown in Figure 3-12, are used for the high pressure lines through the canopy shaker hydraulic circuit components and low pressure lines that return the fluid to the hydraulic reservoir respectively. The entire machine hydraulic system components and the fluid flow direction are shown in Figures A-1, A-2, and A-3.

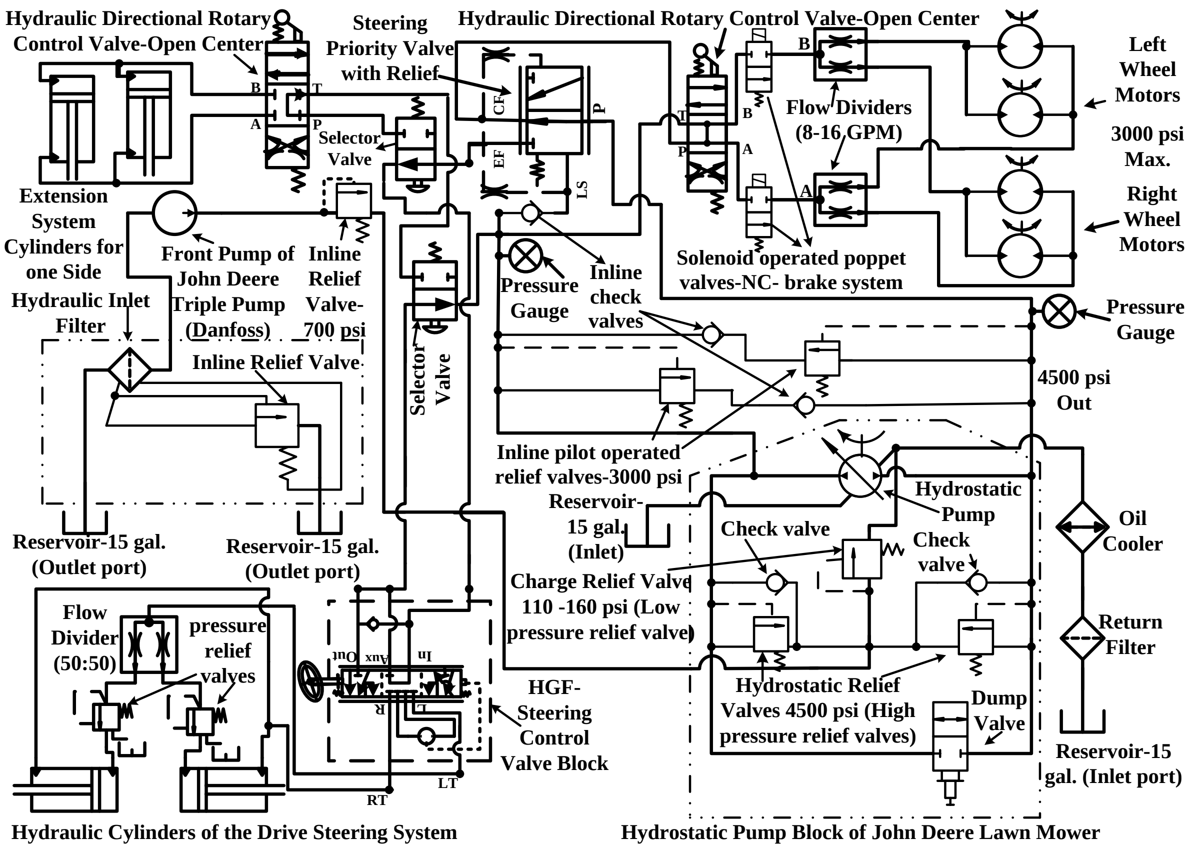

Figure 3-10. Schematic diagram of the hydraulic control system of the self-propelled canopy shaker, two extension systems, and steering system.

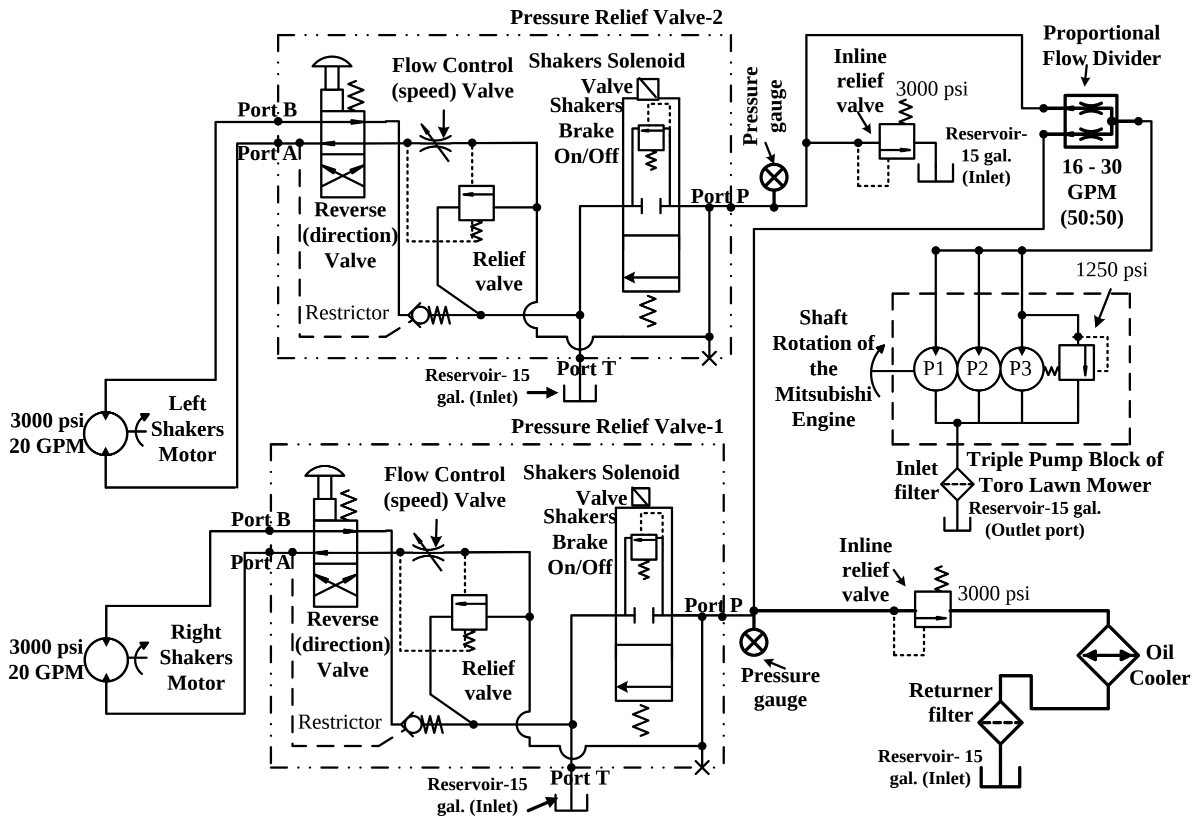

Figure 3-11. Hydraulic control system diagram for the two shaking units of the citrus canopy shaker.

Figure 3-12. Some flexible hydraulic hoses were used for the hydraulic control systems of the citrus canopy shaking machine. [Photos courtesy of Naji Al-Dosary]

The electrical schematic diagram of the Mitsubishi and Yanmar diesel engine ignition systems, and their implementation, are both shown in Figure 3-13 and Figure 3-14. Besides the fuel shutoff solenoid and glow plugs, two 12-volt batteries have been employed to provide power to the electrical starting system circuitry, and to all other electrical components. In addition, de-energizing circuits for the 12-volt On/Off shakers brake solenoids (two solenoid operated directional valves-NC & NO) are added to the electrical wiring diagram of the Mitsubishi engine. Practically, as shown in Figure A-4, the solenoid valve (S1) is a normally closed valve with a nonactuated position (12-volt DC current Off). This valve automatically acts likes a check valve. When the solenoid is energized (12-volt DC current On), effective pressure (700 psi) is permitted to flow through the hydraulic hoses to the shakers motor-brake ports when the solenoid valve (S2) is in a normally open valve position (12-volt DC current Off) to release pressure (release brake) to the hydraulic reservoir. When the solenoid is energized (12-volt DC current On), the pressure is not permitted through it to release the shaker's parking brake.

However, revisions were made, and the hydraulic brake circuits of the crank-shaft motors were eliminated to save more power for the shakers mechanism. Even though the new hydraulic motors for crank-shafts do not have brake ports, the two John Deere relief valve blocks, which include two solenoid valves (On/Off), are utilized to curb the rotational speeds of the two crank-shafts. Otherwise, the speed can be manually controlled by operating the two control valve knobs.

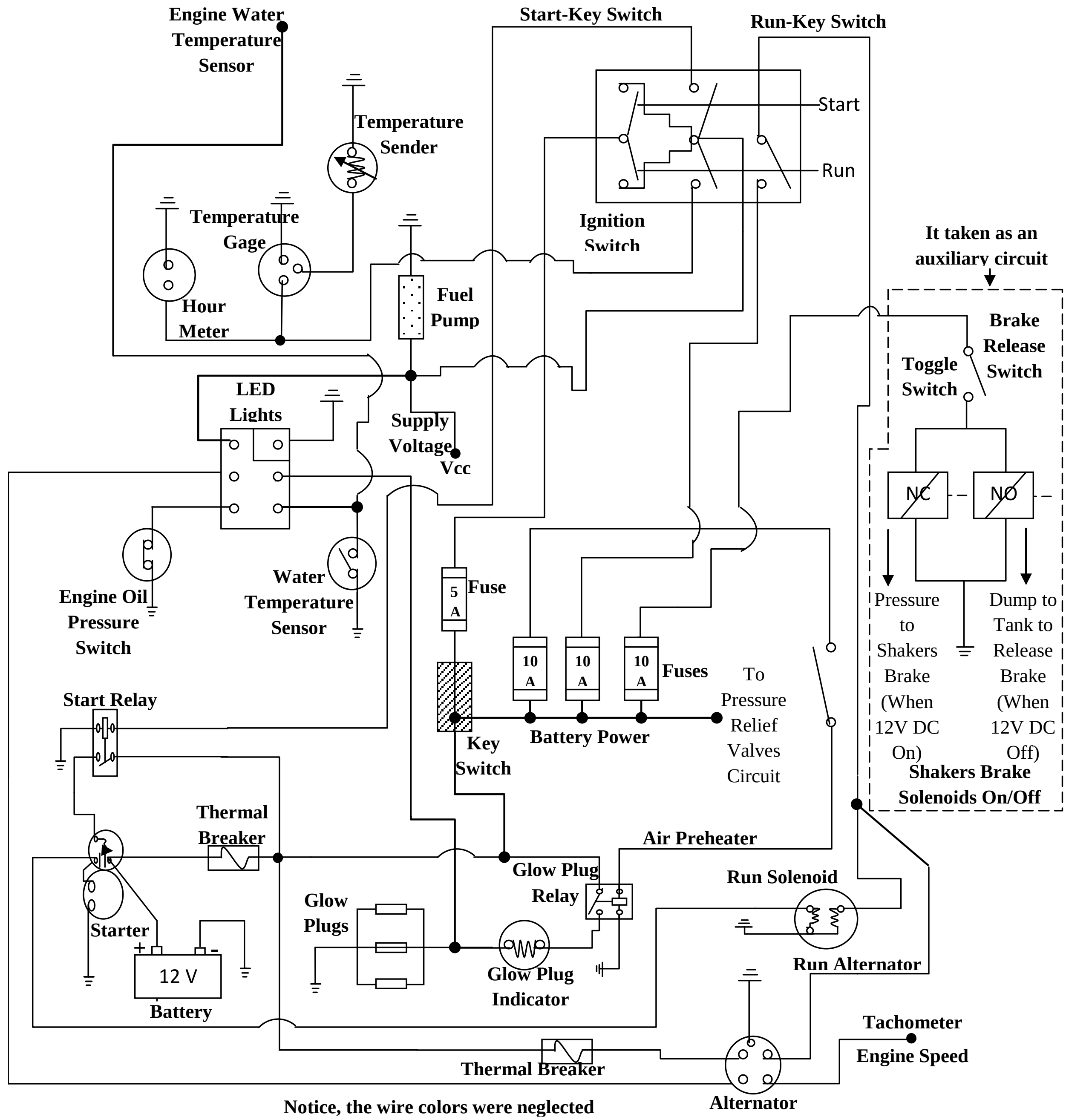

Figure 3-13. The electrical schematic diagram of the Mitsubishi diesel engine ignition system and its implements.

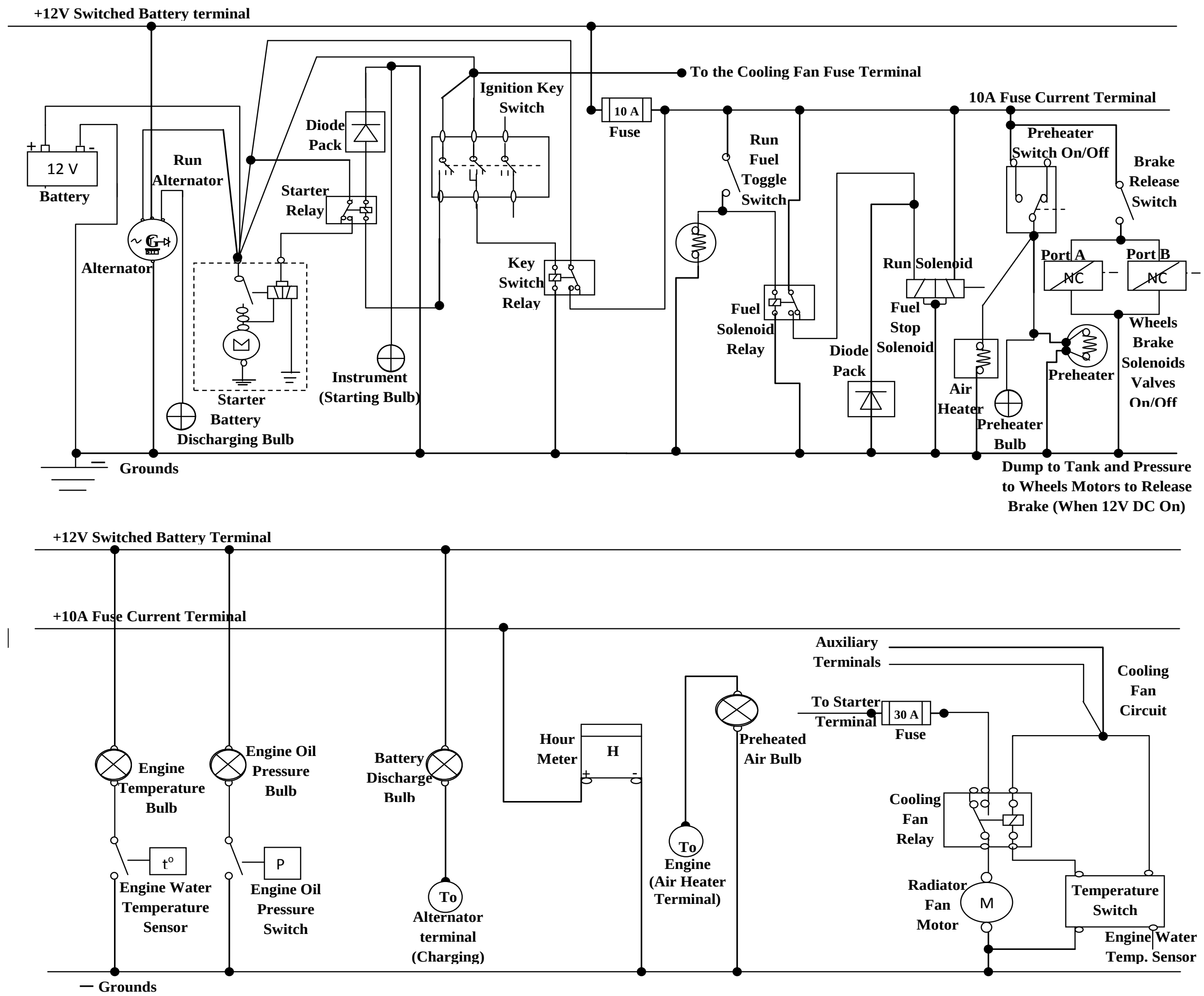

Figure 3-14. The electrical schematic diagram of the Yanmar diesel engine ignition system and its implements with 12 volt on/off wheels brake solenoid valves.

Each shakers' pressure relief valve (John Deere's pressure relief valves), shown in Figure 3-15, contains an On/Off solenoid valve (12-volt DC current), flow control valve (shakers speed control), and forward & reverse switch (directional flow control). To prevent crank-shaft motor's rotation, the hydraulic fluid will be dumped directly to the hydraulic reservoir (release pressure). The flow control valve is used to adjust the crank-shaft motor's rotation to the required rpm for citrus canopy vibration. By using the forward and reverse valve switch (i.e., electrical switch on the control panel), the high pressure flow will be directed to run the crank-shaft motors in backward or forward rotation, as necessary. The shakers' solenoids and forward & reverse switches electrical circuit is appended to the electrical wirings diagram of the Mitsubishi engine (Figure 3-16). Moreover, for quick and easy access to an appropriate control function, the shaker control and Mitsubishi engine instrument panel is positioned directly to the left of the operator's seat. The instrument panel includes an ignition key switch, a bundle of fuses, momentary on/off preheat toggle switch, and a visible indicator LEDs cluster (oil pressure LED, air preheated LED, water temperature LED, and battery discharge LED) as shown in Figure 3-17. Also in order to run the Yanmar engine, the instrument panel led lights are located slightly to the left of the operator's seat (blue/white box). The instrument panel includes an ignition key switch, fuel shutoff solenoid toggle switch, relief pressure valves engagement switches (four toggle switches for the two pressure relief valves), two wheel parking brake toggle switches, and an indicator LEDs cluster (engine oil temperature LED, engine water temperature LED, air preheated LED, and battery discharge LED) as shown in Figure 3-17.

The wheel brake required for locking the machine's wheel motion when the canopy shaker is not in use is regulated by energizing the two solenoid operated poppet valves-NC (S3 & S4) via the two parking brake switches (the solenoids are independent from one another). The

two parking brake switches are located on the control box (blue/white box) positioned on the left side of the operator's seat. On de-energizing these solenoid valves, the hydraulic fluid will be prevented from moving to the four wheel motors and subsequently dumping pressure back to the hydrostatic pump inlet or into the hydraulic reservoir.

Furthermore, two hydraulic steering cylinders (8 inches stroke) are mounted on the pivoting front wheel frames (extended length 23.25 inches, retracted length 15.25 inches, and maximum pressure 3000 psi). These steering cylinders enable a smooth angular turn (left or right) by means of the steering control valve that is connected to the steering wheel. The cylinders allow the machine operator to pivot the front wheels almost 45 degrees in either direction for steering as shown in Figure B-4. The wheel support frame is mounted on bearing spindles, which allow the four tires to turn 360 degrees for special machine tunnel expansion as shown in Figure 3-18. To ensure that both of the front wheels have an efficient synchronized turn without skidding required that a 50%:50% flow divider be installed, which likewise required pressure relief to insure that neither side of the circuit exceeded the system pressure limit. To accomplish this, two inline relief valves were added to the steering control circuit as shown in Figure 3-19. In the current operation, the rear wheels are fixed, and the wheel steering effort is accomplished by the front wheels. A steering control valve (model Toro Reelmaster 5300-D HGF16011 made by TRW, Ross) with its associated steering wheel, is utilized to extend out or retract in the two steering cylinders as shown in Figure B-5.

Two hydraulic circuit selector switches have been inserted into the steering control circuit and the tunnel width hydraulic circuit. Both of these selector switches are utilized to direct the flow of the hydraulic fluid to either the steering hydraulic circuit or the hydraulic circuit for internal tunnel width (width extension or retraction). One of the selector valves (directs high

pressure-P) is positioned at the left side of the operator's seat while the other selector valve (directs a low pressure-T) is on the right side. Four separate cylinders (16 inches stroke), which are connected in series, are controlled by the hydraulic directional control valve (joystick handle) for extension or retraction of the harvesting tunnel width. Because the load of the two engines is concentrated at the rear part of the harvester body, the two large size cylinders (3.25 inches bore size) were located at the rear of the machine structure while the two small size cylinders (3 inches bore size) were located at the front. To operate the hydraulic steering circuit, the knob of the right selector valve is fully pulled up, while the knob of the left selector valve is wholly pushed down. Otherwise, for the extension cylinders functions, the knob of the right selector valve is pushed down, while the knob of the left selector valve is pulled up, thus releasing the hydraulic fluid pressure while the hydraulic steering circuit is idle. Basically, the steering hydraulic circuit should always be synchronized with the hydraulic circuit of the four wheels drive.

The weight of the self-propelled canopy shaking machine, which requires a single operator, has a gross weight of approximately 7500 lb. Design of the prototype continuous citrus canopy shaking machine is shown in Figure B-1. Also, this new design provides for easy transportation as shown in Figure B-3.

Figure 3-15. The John Deere's pressure relief valve (shakers' pressure relief valve). [Photos courtesy of Naji Al-Dosary]

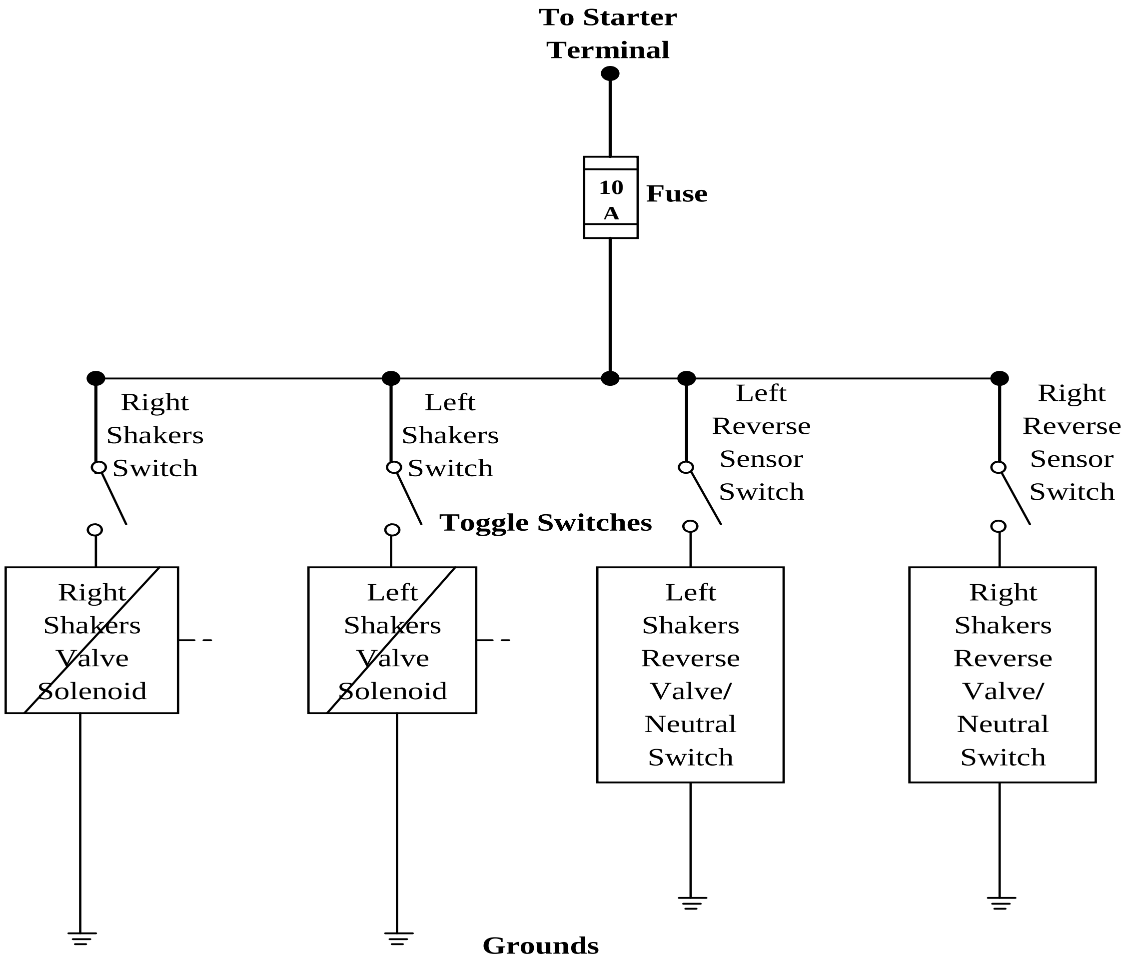

Figure 3-16. Electrical operating circuit of the right and left John Deere's pressure relief valves (shakers brake).

Figure 3-17. Electrical instrument panels of the citrus canopy shaking machine. [Photos courtesy of Naji Al-Dosary]

Figure 3-18. Movable wheels frames of the citrus canopy shaker with carrier bearing hinge (spindle). [Photos courtesy of Naji Al-Dosary]

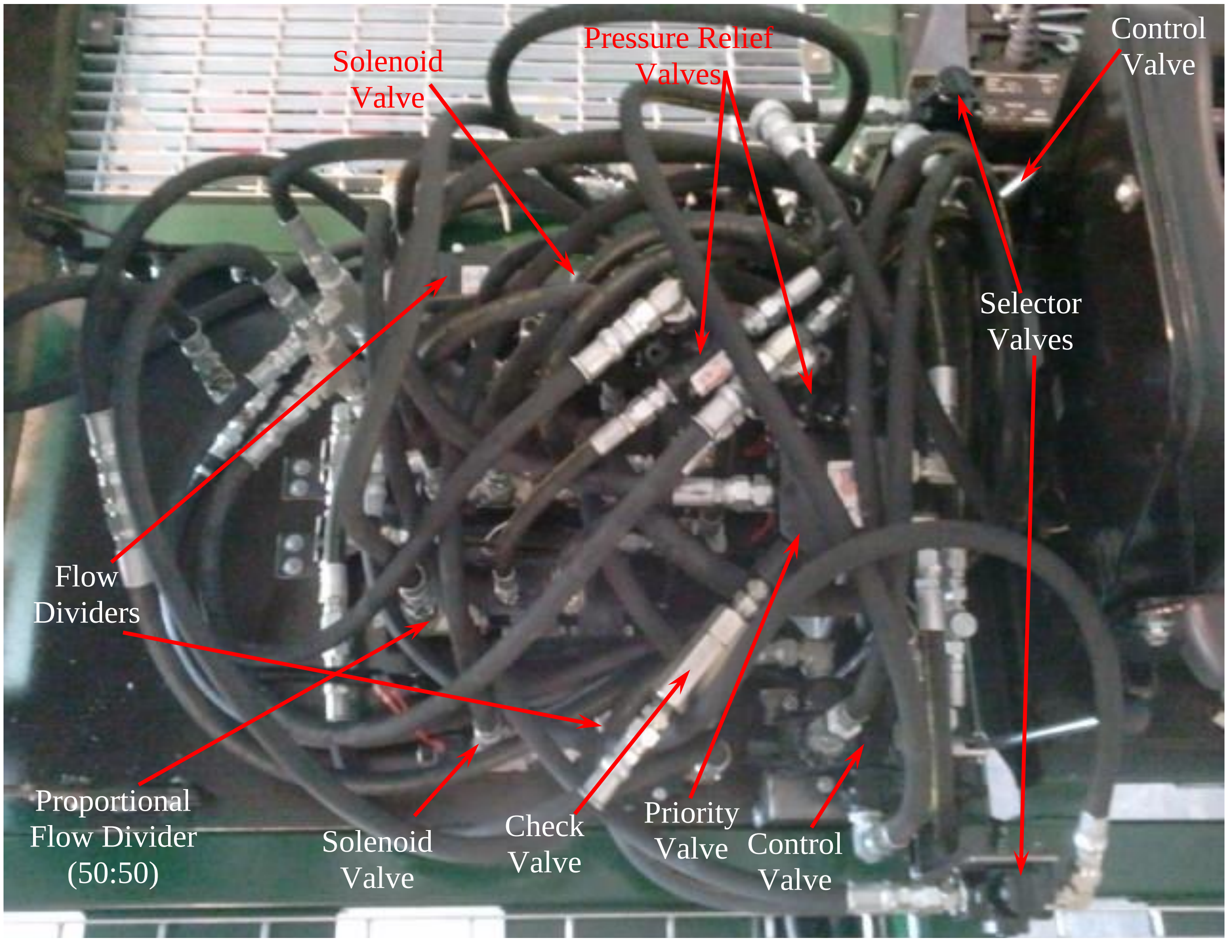

Figure 3-19. Some hydraulic system components of the preliminary self-propelled canopy shaker transport speed located behind the operator's seat. [Photo courtesy of Naji Al-Dosary]

Harvester Modifications for the Final Performance Tests of the Citrus Shaker Harvesting Machine

The main objective of this dissertation research was to develop an effective mechanical harvester for semi-dwarf citrus trees. So, a prototype self-propelled citrus canopy shaker machine was designed and tested on grapefruit trees that were harvested in the summer-2013. The harvesting efficiency of the preliminary design did not provide enough information to make a valid decision about the machine's performance. The maximum value of the fruit detachment rate was 58.06 %, while the maximum average of the fruit detachment percentage was 41.58 %. So, to design a more effective mechanical citrus harvesting machine, some modifications were made to the preliminary harvester design. The final prototype citrus harvesting machine is presented in Figure 3-20. Accordingly, the modifications made to the shaker machine are discussed in the following section.

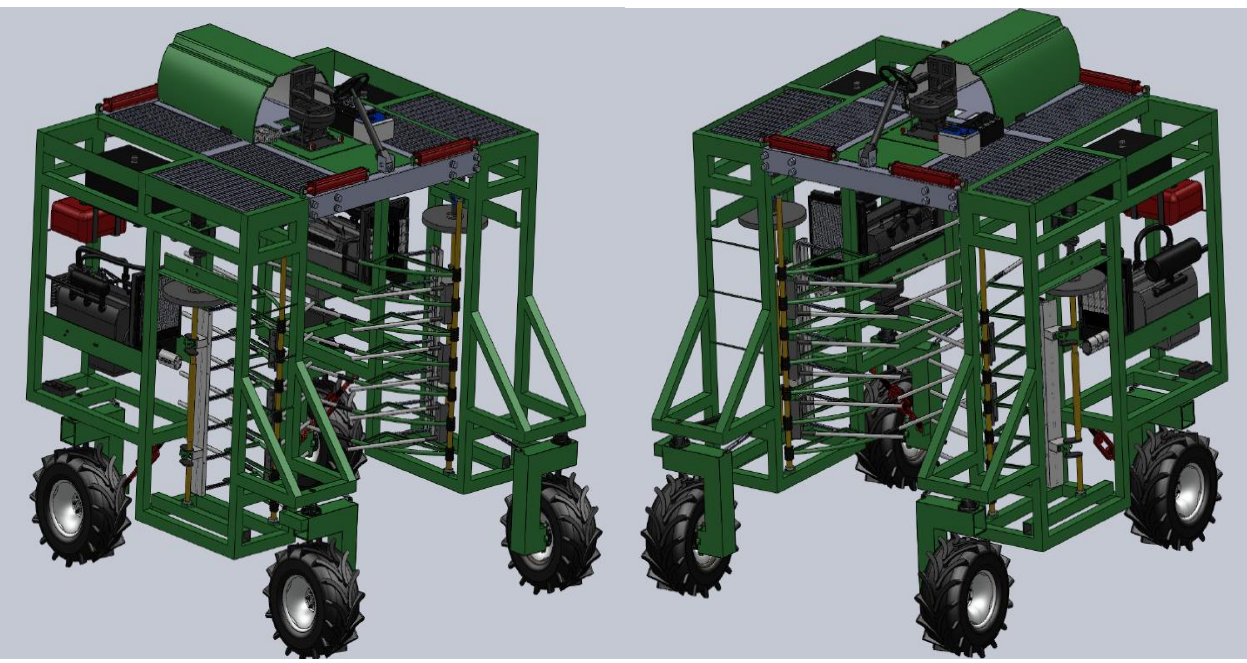

Figure 3-20. Final prototype citrus canopy shaking machine.

For the final performance trials of the canopy shaking machine, the hollow gray PVC pipes were replaced by flexible 1 inch OD and 0.50 inch ID UHMW polyethylene white pipe 30

inches in length, with 3 inches inserted into a 6 inch steel coupling pipe. The other end of the steel coupling pipe was installed onto 3 inches of the steel beater pipe. This was done to avoid fatigue that may occur when using high shaking speeds. Also, to insure that tube is connected securely to the steel beater pipe, a 24 inch long solid steel bar was installed into one end of the flexible pipe and the other end of the steel beater pipe. The total length of the beater was increased to 58 inches. Also, 12 UHMW hollow rods (length of 30 inches, OD 1 inch, and ID 0.50 inch) were attached to the shaking system by mounting 3 pairs of extra beaters on the main steel pipe of each shaking unit as shown in Figure 3-21. The additional beater is designed to work at an angle with the original beater position, and the vertical distance between each beater on each shaking unit is 3.50 inches. Therefore, each shaker's unit now had 13 beaters, which were arranged vertically and extended horizontally.

A  B

Figure 3-21. New extra beaters attached to the original shaking beaters. A) Rear view of the machine and B) the machine front view. [Photos courtesy of Naji Al-Dosary]

Also, to more easily adjust each engine's speed by its throttle, a push-pull throttle with associated thread lock and knob was relocated underneath the harvester operator's seat, as shown in Figure 3-22.

The Eaton hydrostatic pump, which has a swash-plate mechanism, shall be adjusted manually by using a single lever handle. The hand regulator was also relocated underneath of the right side of the harvester operator's seat, as shown in Figure 3-23. Using the swash-plate of the hydrostatic transmission, the operator can change the speed range of the machine, and this transmission pump also provides a dynamic brake that can easily stop the harvester movement. In addition, changing the swash-plate direction (reverse or forward), will correspondingly change the direction of movement of the shaking machine.

Figure 3-22. New position of the harvesting machine control systems. [Photo courtesy of Naji Al-Dosary]

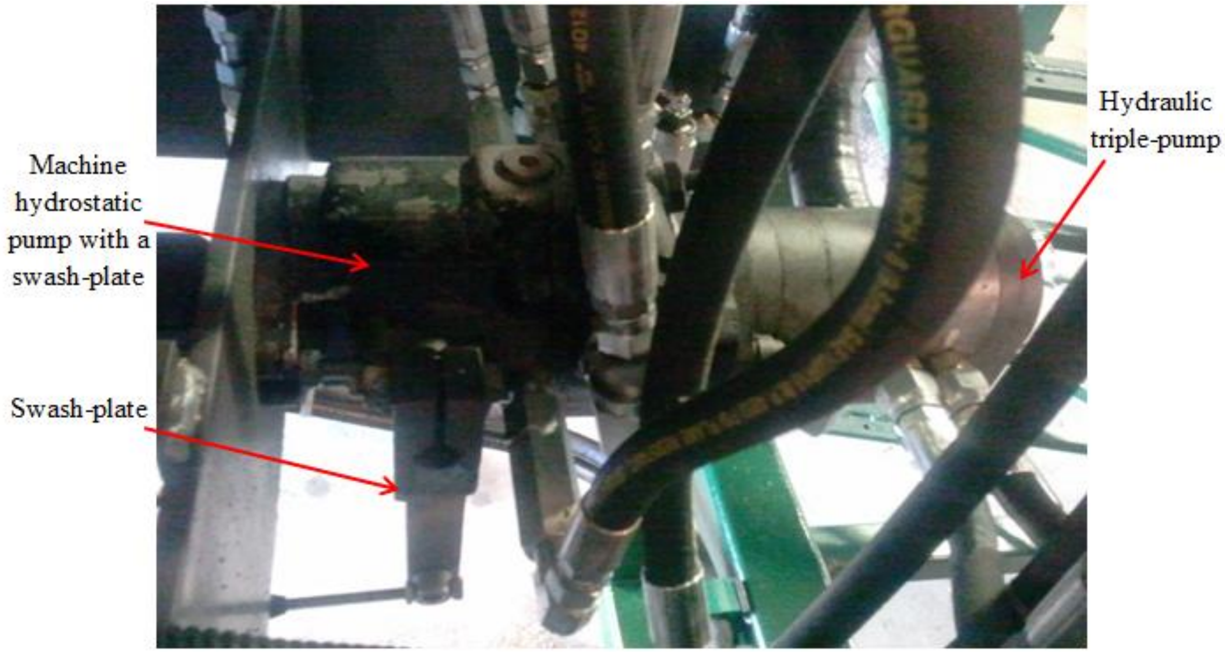

Figure 3-23. Eaton hydrostatic pump with a swash-plate mechanism for the harvesting machine wheels drive. [Photo courtesy of Naji Al-Dosary]

In order to reduce the length of the crank-shaft, the three cranks on the original vertical motor shaft (crank-shaft) were trimmed and redesigned to have two cranks (3 inches throw radius), which were then mounted on a solid steel shaft of total length 54 inches and 1.50 inches in diameter. To insure that the crank-shaft was strong enough, the original central crank was replaced with shorter shaft of a total length of 16 inches and diameter of 2.50 inches. Each vertical motor shaft is supported by a flange bearing at the bottom (2 bolt flange bearing), and a shaft coupling at the top end, as well as having the flywheel mounted to the crank-shaft by a steel flange. A steel shaft (length of 12 inches and OD 2 inches) with two steel flanges welded on each end was used to connect the flywheel to the hydraulic motor of the shakers. Meanwhile, the flywheel was lowered from the hydraulic motor about 14 inches as shown in Figure 3-24 A. Also, to have a smoother shaft rotation, a split pillow block bearing (2 inches, ID) was used to support the crank-shaft on the harvester body (Figure 3-25).

A B

Figure 3-24. Crank-shaft (motor shaft) of the citrus harvesting machine. A) The final crank-shaft design and B) preliminary crank-shaft design. [Photos courtesy of Naji Al-Dosary]

Figure 3-25. A new vertical motor shaft (crank-shaft) with a flywheel supported by pillow block bearing. [Photo courtesy of Naji Al-Dosary]

The final modification of the shaking machine involved the hydraulic control system of the self-propelled 4 wheel drive system. The original pre-test design of the harvester (preliminary design) had 2 solenoid operated poppet valves-NC for the brake system. These were removed since wheel motor leakage prevented proper braking (Figure 3-26). Also, to gain additional power for the 4 wheel drive, the pressure line of the steering pump and the harvester tunnel extension cylinders were plumbed directly to the rear pump of the John Deere triple pump. Now, the rear pump of the Danfoss triple pump supplies the hydraulic fluid flow to the four hydraulic cylinders for extension or retraction of the tunnel width of the harvester, and also the steering pump. The low pressure of this circuit will go back directly to the reservoir. The schematic diagram of the hydraulic control system of the shaker units' extension and steering system is shown in Figure 3-27. On the right side of the operator's seat, a two spools directional control valve (dual lever handles) was placed to control the harvester internal tunnel width. The extension cylinders on each side will now be handled by one lever handle, as presented in Figure 3-22. The front pump of the triple pump now supplies the charge flow to the hydrostatic transmission pump for the four wheel drive motors. Meanwhile, the low pressure of this circuit will go back to the inlet ports of the hydrostatic transmission pump, or to the reservoir. The schematic diagram of the hydraulic control system of the self-propelled 4 wheel drive system is shown in Figure 3-28. Finally, Figure B-2 shows the final design of the continuous citrus canopy shaking machine.

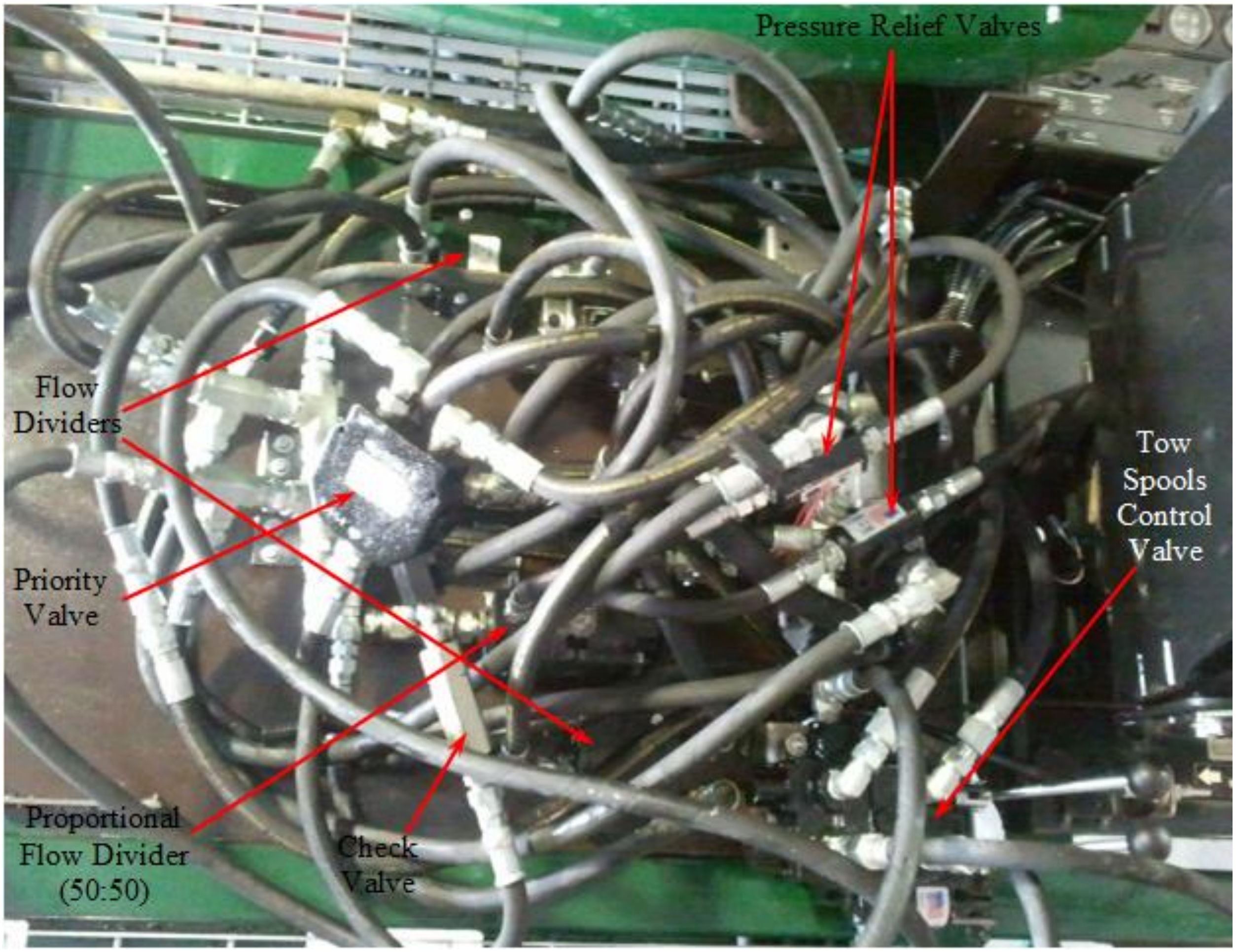

Figure 3-26. Some components of the hydraulic system of the preliminary design have been reduced in order to provide some power for the final design of the canopy shaker. [Photo courtesy of Naji Al-Dosary]

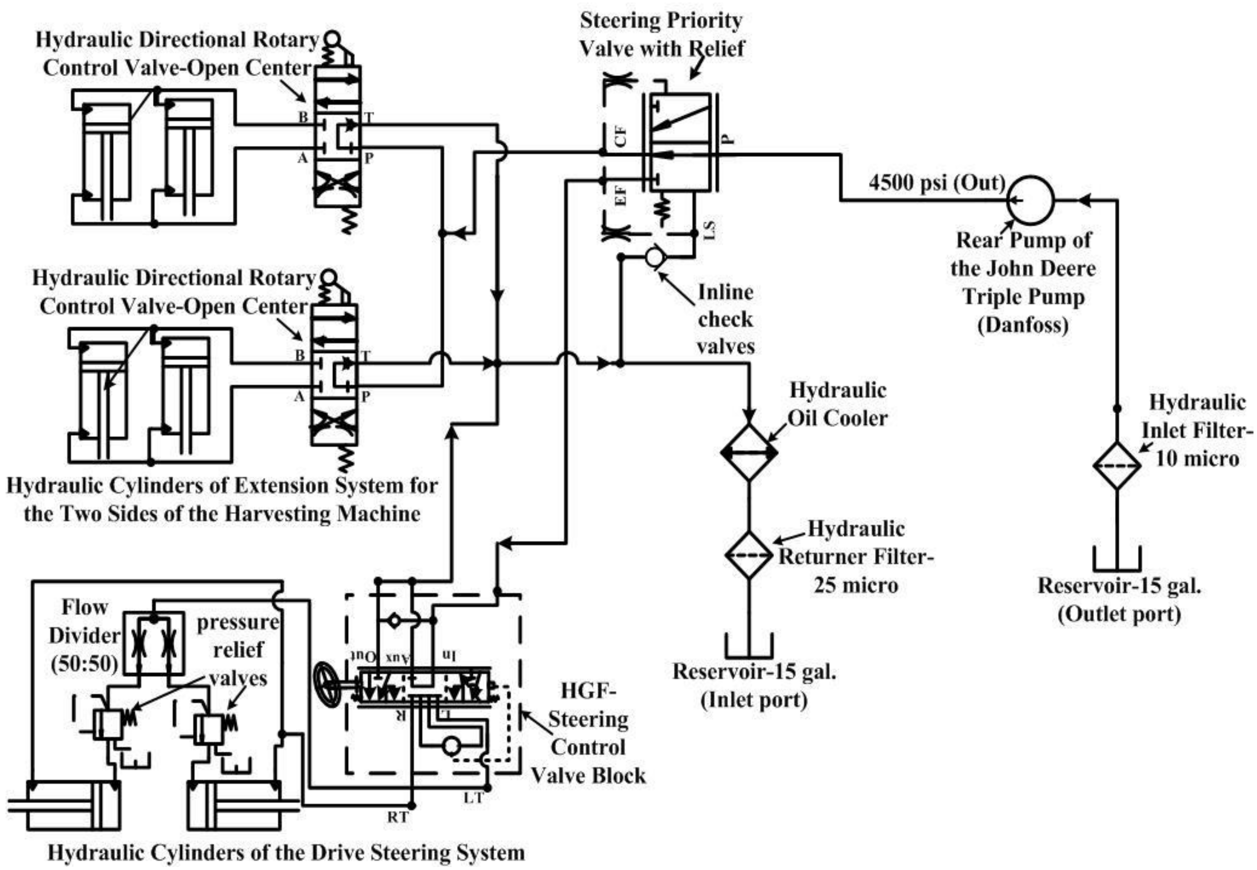

Figure 3-27. Schematic diagram of the hydraulic control system of the two canopy shakers units' extension, and steering system for the final harvester design.

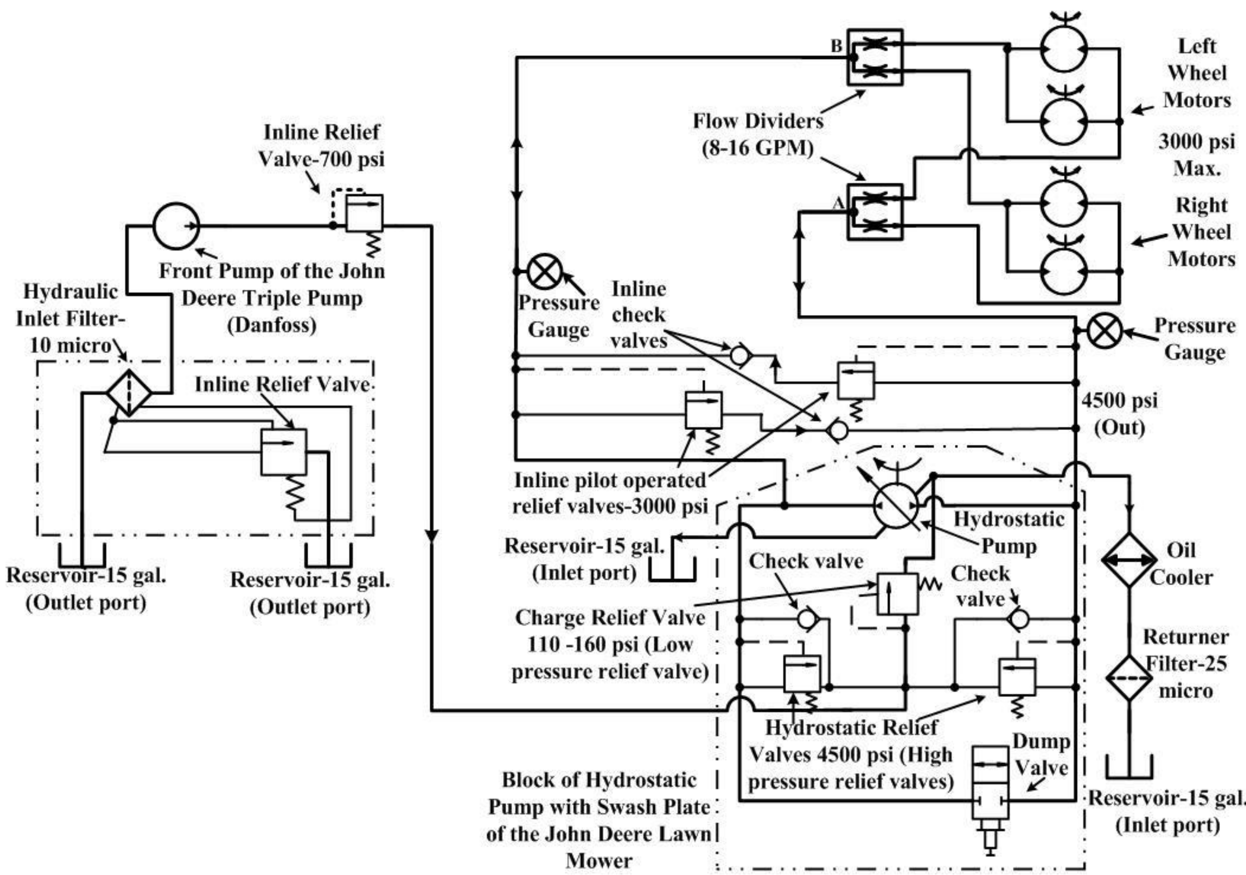

Figure 3-28. Schematic diagram of the hydraulic control system of the self-propelled canopy shaker transport speed for the final harvester design.

The Intended Field of the Citrus Fruit Trees

Field experiments for the canopy shaking machine performance evaluation were accomplished at a citrus grove at the Plant Science Research and Education Unit of the University of Florida, 20 miles south of the City of Gainesville, at Hawthorn Prairie, Marion County, Florida (+29° 24' 28.50" N, -82° 08' 22.10" W). The grove included the following varieties, Hamlin, Valencia, and Ray Ruby scions. As desired, the citrus hedges had been arranged in spacing of 10 ft × 20 ft for Valencia strain and 12 ft × 20 ft apart for the Hamlin strain (Figure 3-29). However, these were not dwarf trees and thus exceeded machine height capacity. To determine proper machine operations, and improve the harvest efficiency of the shaker machine, the first trials (pre-test) were performed on the grapefruit trees (Ray Ruby scion), which were dwarfed to less than 10 feet tall, as shown in Figure 3-30. In May and June, 2013 (90^{o} F approximately) the late-season harvest of the Ray Ruby grapefruit (2012-13) was completed, with the new season fruit starting to emerge on the trees. The grapefruit hedges had been arranged in a space of 8 ft between trees and 20 ft between rows, with average productivity of the grapefruit orchard of 55,143.00 fruits per hectare (approximately 25 ton/ha or 78 fruits/tree in average yields). Furthermore, the branches of the oranges and grapefruit trees varied significantly as presented in Figures 3-31 and 3-32. Most of the trees had low hanging branches reaching to the field soil. Nevertheless, skirting and pruning were done on the grapefruit tree's canopies to adjust the canopy height to be about 8 ft and width of nearly 7 ft.

The field experiments of the final prototype harvester design were executed on the same Ray Ruby orchard, to determine the harvesting machine performance improvements. The final trials were performed on January 6, 2014 (51^{o} F), which was the winter-season harvest of the Ray Ruby grapefruit (2013-14), with average productivity of the grapefruit orchard of 76,020.00 fruits per hectare (approximately 34.48 ton/ha or 113 grapefruits/tree in average yields). Before

harvesting, the branches of the grapefruit trees were skirted and pruned on November 18th of 2013, to set the canopy height and width to nearly the actual size of the internal dimensions of the harvesting machine (Figure 3-33). Furthermore, a small percentage of the grapefruit production was lost as a result of the pruning process, as shown in Figure 3-34.

Figure 3-29. Citrus field (Oranges) in the PSREU at UF, 09/22/2011. [Photo courtesy of Naji Al-Dosary]

Figure 3-30. Citrus field (Grapefruits) in the PSREU at UF, 05/24/2013. [Photo courtesy of Naji Al-Dosary]

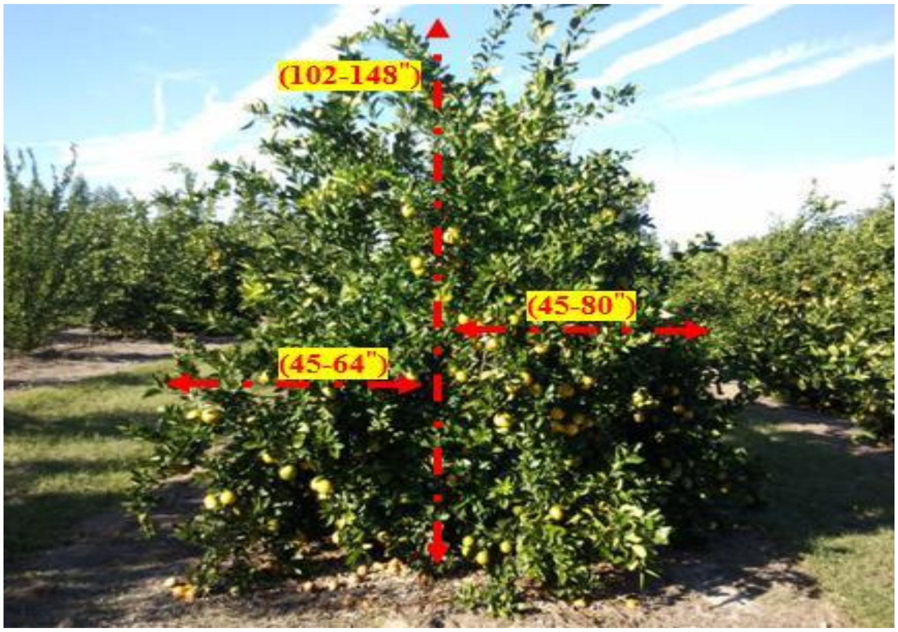

Figure 3-31. Longitudinal and lateral extension of the branches of the orange trees. [Photo courtesy of Naji Al-Dosary]

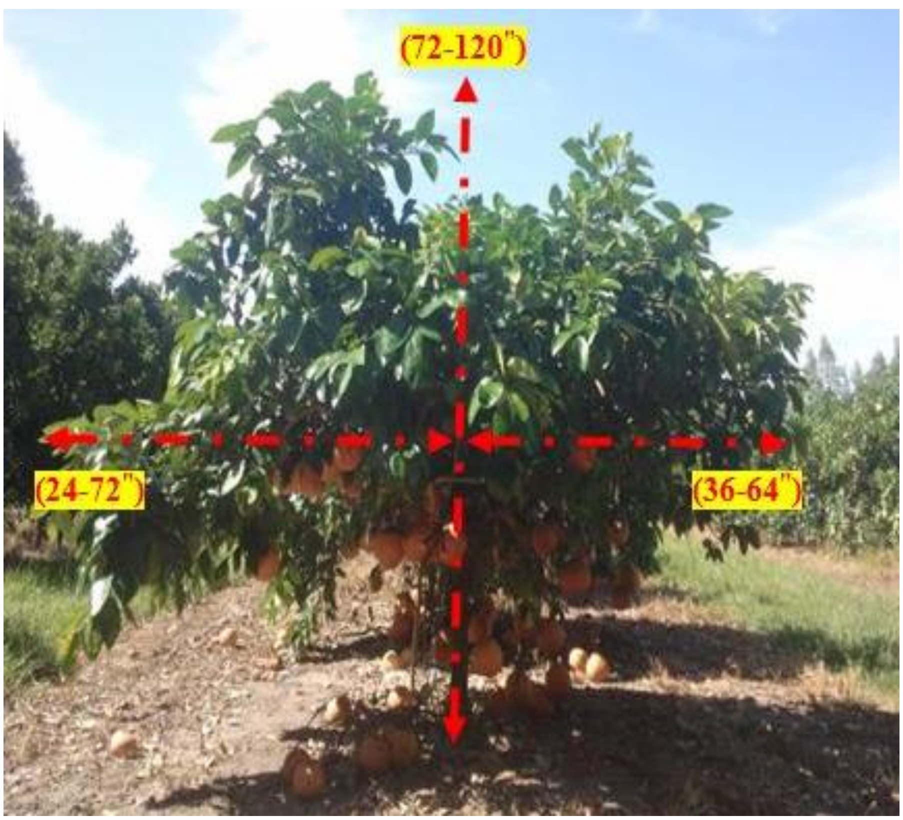

Figure 3-32. Longitudinal and lateral extension of the branches of the grapefruit trees. [Photo courtesy of Naji Al-Dosary]

A B

Figure 3-33. Grapefruit trees in the PSREU field. A) Grapefruit trees before pruning and B) the grapefruit trees after the pruning process. [Photos courtesy of Naji Al-Dosary]

A B

Figure 3-34. Grapefruit trees in the PSREU field after pruning process. A) Pruning was done underneath the grapefruit canopies and B) grapefruits were dropped out of the canopies because of the canopies pruning. [Photos courtesy of Naji Al-Dosary]

A study was conducted prior to the harvesting period for the season of 2013-14, where fruit pulling forces were measured to see if they could distinguish the fruits' maturity on the tree canopies. Aside from color change, an indicator of grapefruit ripeness may be the lowest fruit pulling force. Although unripened grapefruit will continue to ripen after harvesting, when the fruit is ripest provides the best time for fruit harvesting, and allows the fruits to snap easily from the tree. Figure 3-35 and Table 3-3 shows the variety of the fruit pulling forces which were measured on the grapefruit trees. The maximum pulling force was 30 lb_f and the minimum fruit pulling force was 6.75 lb_f, while the average of the pulling force was 19.15 lb_f. The final trials of the improved harvester design (final-test) were performed on January 6th, 2014.

Table 3-3. Variety of the fruit pulling forces which were measured on the intended grapefruits.

Treatments	Date 2013/2014	Temperature F^{o}	Fruit pulling force lb_f Min.	Max.	Ave.
1	11/11	70	11	29	19.80
2	11/18	68	20	28.50	24.10
3	11/20	60	15	25	21.80
4	11/25	62	13	26	18.80
5	11/27	55	11	21	16.30
6	12/01	71	10	22	17.00
7	12/04	83	6.75	15	12.45
8	12/09	86	14	20	16.80
9	12/12	62	14	23	18.40
10	12/15	63	15	30	22.20
11	12/18	51	14	19	16.20
12	12/22	85	20	30	24.20
13	12/25	72	15	23	19.60
14	12/29	68	16	25	20.40
15	1/2	68	12	26	18.20
16	1/5	83	16	26	20.20
		Average			19.15

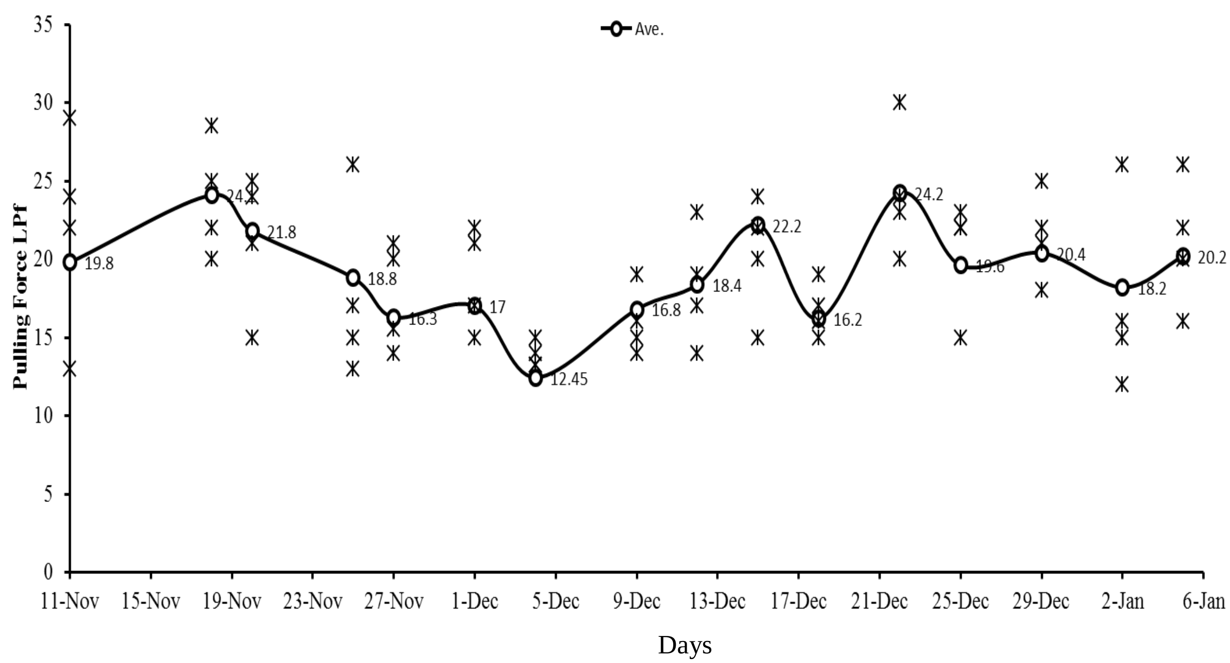

Figure 3-35. The grapefruit maturity before the harvesting period of the season of 2013-14.

Theoretical Analysis of the Tree Branches Deflection

In general, most of the previous scientific research (i.e., experimental or theoretical research) done on plant harvesting, was done to create techniques to direct the appropriate oscillation toward the target trees. Whichever harvesting approach was used to produce tree oscillations (trunks or branches shaking machine), the ones that were able to optimally transfer those oscillations to trunks or branches resulted in the highest percentage of fruit harvested. Lately, in Florida citrus groves, three contemporary harvesting systems (TSC, CCSC, and T-CS) have been deployed to remove citrus fruits from the bulk of citrus trees.

Subsequently, distribution of the adequate tree limb loads (w), which are directed by the beaters of the canopy shaker, can be represented as a homogenous load distribution subjected on a clamped-free beam as expressed in Figure 3-36. Therefore, by determining the fundamental deflection equation, the vertical deflection δ_y at any position of *x* on the cantilever beam can be calculated as (AWC, 2007):

By deeming any *x*-section that posts a distance x from the free end of beam, the solution of the beam deflection is supposed to be:

For the clamed-free beam, the bending moment equation is defined as:

$$M = \frac{1}{2} w x^2 \tag{3-7}$$

In addition, the bending moment can be identified by:

$$M = \frac{d^2 y}{dx^2} \; EI \tag{3-8}$$

$$Thus, \frac{M}{EI} = \frac{d^2 y}{dx^2} \tag{3-9}$$

Particularly, the boundary conditions at the beam fixed end ($x = \ell$) and free end ($x = 0$) will be considered. So, for the beam position at the fixed end ($x = \ell$), the boundary condition where no obvious deflection will be is:

$$y = 0 \tag{3-10}$$

$$\frac{dy}{dx} = 0 \tag{3-11}$$

Moreover, from the other side, where the free end ($x = 0$) of the cantilevered beam, the boundary condition where no bending moment is:

$$\frac{d^2y}{dx^2} = 0 \tag{3-12}$$

Therefore, by substituting the bending moment in term of x, the second differential equation will be:

$$\frac{d^2y}{dx^2} = \frac{M}{EI} = \frac{wx^2}{2EI} \tag{3-13}$$

Thus, by integrating the second deferential equation, the first deferential equation will be symbolized as:

$$\frac{dy}{dx} = \int_0^x \frac{d^2y}{dx^2} = \frac{w}{2EI}\int_0^x x^2 dx = \frac{w}{6EI}x^3 + c_1 \tag{3-14}$$

Besides, by integrating the first deferential equation, the beam deflection equation will be obtained as:

$$y = \int_0^x \frac{dy}{dx} = \frac{w}{6EI}\int_0^x x^3 dx + \int_0^x c_1\, dx = \frac{w}{24EI}x^4 + c_1 x + c_2 \tag{3-15}$$

From the equations (3-14) and (3-15) with the boundary conditions at the fixed end of the clamped-beam, the values of the constants c_1 and c_2 are:

By taking the first derivative of *y* and equal to zero, will obtain:

$$y = \frac{w}{24EI} x^4 + c_1 x + c_2 \tag{3-16}$$

$$Then, \quad \frac{dy}{dx} = \frac{w}{6EI} x^3 + c_1 = 0 \tag{3-17}$$

$$Thus, \quad c_1 = \frac{-w}{6EI} x^3 \tag{3-18}$$

Moreover, by substituting c_1 into equation (3-16) and replacing $x = \ell$ also setting the result equal to zero, will obtain:

$$y = \frac{w}{24EI} x^4 + c_1 x + c_2$$

$$y = \frac{w}{24EI} x^4 - \frac{w}{6EI} x^3 x + c_2 = 0 \tag{3-19}$$

$$c_2 = \frac{-w}{24EI} x^4 + \frac{w}{6EI} x^4 = \frac{-w}{24EI} \ell^4 + \frac{w}{6EI} \ell^4$$

$$c_2 = \frac{w}{6EI} \ell^4 - \frac{w}{24EI} \ell^4 = \frac{4w\ell^4 - w\ell^4}{24EI} = \frac{3w\ell^4}{24EI}$$

$$Thus, c_2 = \frac{w\ell^4}{8EI} \tag{3-20}$$

Subsequently, by substituting the equations of the two constants c_1 and c_2 into equation (3-15), the ultimate vertical deflection of the clamped-free beam (δ_y) at any value of *x* with homogenous load distribution assumed to be:

$$\delta_y = \frac{w}{24EI} \left(\mathrm{x}^4 - 4\ell^3 x + 3\ell^4 \right) \tag{3-21}$$

In addition, the maximum deflection (δ_{ymax}) at the free end of the clamped-free beam where *x* will be equal to zero ($x = 0$) is supposed to be:

$$\delta_{y_{\max}} = \frac{w\,\ell^4}{8EI} \tag{3-22}$$

Where, E is the tree limbs modulus of elasticity and I is a constant area moment of inertia of the limbs.

Thus, E modulus of elasticity calculation will be resulted as:

$$E = \frac{F\,\ell_o}{A\,\Delta\ell} \tag{3-23}$$

Where, F is the force applied to the limb, A is the cross-section area, ℓ_o is the original length of the limb before applying the force, and $\Delta\ell$ is the change in the length of the limb after applying the force.

Therefore, I, the area moment of inertia calculation assumed to be when the limb takes a circular cross section as:

$$I = \frac{\pi\,{D_f}^4}{64} \tag{3-24}$$

Where, D is the limb diameter.

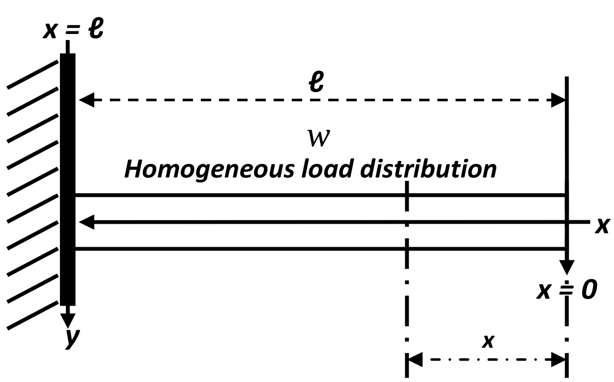

Figure 3-36. A homogeneous load distribution lying on a clamped-free beam.

Field Measurements Procedure

Mechanical harvesting is employed generally to shorten the harvesting time and raise the field crop productivity. Therefore, there are two types of harvesting systems used in Florida citrus farms, depending on the shaking approach used (e.g., shake the tree canopy or shake the trunk of tree, causing the fruit to fall out from the tree stems). For the citrus harvesting, mechanical harvesting utilizes the generation of a moderate vibration into the tree canopy. Accordingly, the fundamental component of the canopy shaker is optimally shaking the beaters to impart those oscillations efficiently to the citrus tree canopies, thus maximizing the harvested fruit yield. So, measurements were performed during the operation of the shaking machine in the citrus field (Figure 3-37), to determine the necessary shaking speed for fruit dislodgement when the beaters are vibrating, the acceleration of the tree limbs as a result of the shaking action, the harvesting width for the beaters' penetration, and the injuries caused to the tree's branches. The dislodged fruits, which fell on the field ground, and the citrus fruits that are remained on the trees, were collected manually.

Figure 3-37. The preliminary citrus canopy shaking machine through its harvesting performance in the summer harvest of 2013. [Photos courtesy of Naji Al-Dosary]

The essential harvesting measurement procedures that were used throughout this study will be shown in the following sections.

Procedures for Estimating the Values of the Tree Canopy Acceleration Magnitude

An accelerometer is often utilized for diverse applications where it is considered for vibration, acceleration or shock analysis. It is often used with the fast Fourier transform (FFT) algorithm for analyzing the vibration data results (sampled signals), regardless of the variation in the vibration frequency. The measurement of acceleration can be applied to different spots in the tree canopy (branches or fruits) for measuring acceleration in the fruit, which can be correlated to fruit detachment. Trees were instrumented using Triaxial USB Accelerometers, model X16-1C (GCDC) that have an amplitude range up to ±16 g, sample rates up to 200 Hz, and weigh 55 gm with the associated battery. The accelerometer power was supplied by a detachable AA battery (1.5A) or a +5 volt PC power supply. For field acceleration data recording, an easily removable 2 GB card is built-in (self-memory storage). Fortunately, the GCDC X16-1C Triaxial USB Accelerometer does not require an intricate supplement data acquisition device for transmitting the acceleration data to the portable computer or special software program (USB terminal interface is included). The raw acceleration data (a mixture of time and voltage data) was obtained as a stream of instantly recorded numbers, which were written, viewed, and analyzed through the creation of a text-file and x, y, and z-axis figures by either Microsoft Excel or WordPad. The test file of the acceleration data, which is actually a built-in application of the XLR8R, is compliant with java programs (Java (TM) Platform Standard Edition 6.0), as revealed in Figure 3-38. Through the XLR8R java application, the acceleration analysis was shown in graphical plots as a function of time (g-force vs. time). Later, the fast Fourier transform (FFT) was utilized as necessary, to gather data on the frequency response of the shaking beaters of the

harvester or branches of the grapefruit canopy. This data was displayed as a plot of the power spectrum versus frequency response (time signal and frequency spectrum graphs).

Before testing began, 15 USB accelerometer sensors model X16-1C were randomly placed on various branches at different locations in the canopy of the fruit tree (Ray Ruby grapefruit), and attached using plastic adhesive tape. The 15 USB accelerometer sensors were used to estimate the dynamic acceleration (acceleration magnitude) during the harvesting operations, as shown in Figure 3-39. Moreover, a rotational speed instrument (digital tachometer) was utilized to obtain the rotational speeds of the crank-shaft (rpm) and the beater's rotational speeds (shaking speeds, in/sec) during the various harvesting operations. For precise data analysis of the most important measurements, the practical gravitational accelerations (a_i) on the citrus tree branches for each axis (i^{th}) of the three orthogonal axes coordinates (x, y, and z-axis) from each X16-1C acceleration sensor, were developed using the Java XLR8R program. Subsequently, the resultant of the magnitude of the acceleration data (a_T) could be calculated by using the following equation of the RSS method (Bedford and Fowler, 1995).

$$\text{The acceleration magnitude, } a_T(g) = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (3\text{-}25)$$

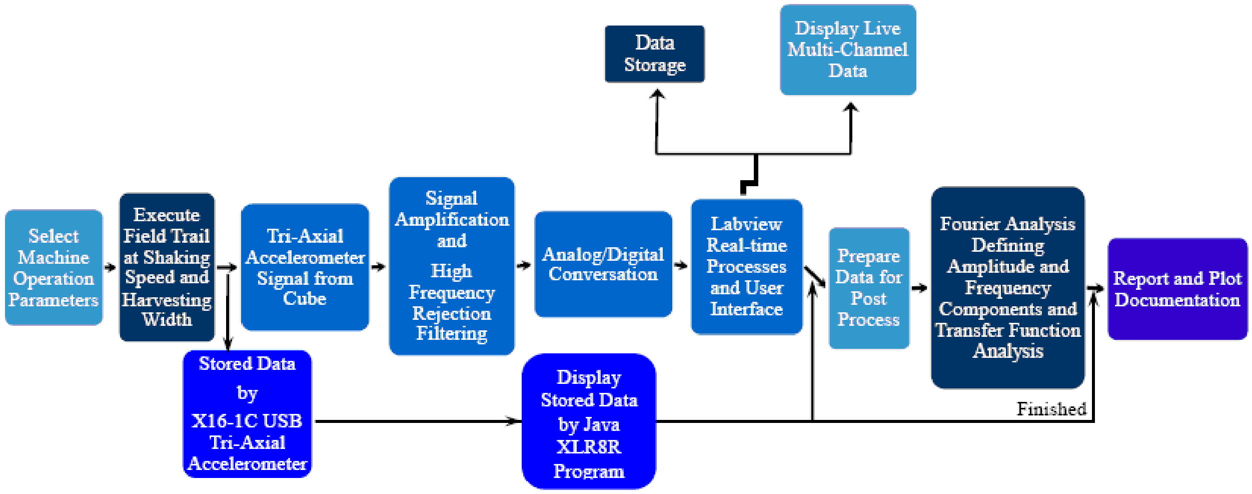

Figure 3-38. An organization chart of the vital acceleration processes for data gathering.

Figure 3-39. Some of the X16-1C acceleration sensors attached to some citrus tree branches. [Photos courtesy of Naji Al-Dosary]

The ordinary distance at point (a) and the beater end spot (A), as shown in Figure 3-40, can be determined by using a proper displacement of the slider-crank formula (Srivastava et al., 2006). So, the regular amplitude at the jointing point (a) of the shaking beater and reciprocating rod (turn buckle) will be:

$$\text{a}\ (in) = r\left(1-\cos\theta\right)+\ell-\sqrt{\ell^{2}-\left(r\sin\theta\right)^{2}} \qquad (3\text{-}26)$$

Where: a is the beater displacement at the jointing point of the beater and the coupling (turn buckle) link (inch), r is the radius of the crank (inch), ℓ is the length of the reciprocating rod (inch), and θ is the angular displacement of the crank (radian).

Then, from the basic beater length ratio, the amplitude at the beater free end (A) would be resulted by:

$$\frac{\ell_1}{(\ell_1 + \ell_2)} = \frac{\mathrm{a}}{A} \tag{3-27}$$

$$A(in) = \mathrm{a}\left(\frac{(\ell_1 + \ell_2)}{\ell_1}\right) \tag{3-28}$$

Finally, the typical beater's speed (S_a) at the jointing point (a) of the beater and reciprocating rod (turn buckle) is presented by the subsequent equation (Srivastava et al., 2006):

$$S_a\left(\frac{in}{\sec}\right) = \dot{\theta}\left((r\sin\theta) + \frac{r(\sin\theta)(\cos\theta)}{\sqrt{\left(\frac{\ell}{r}\right)^2 - (\sin\theta)^2}}\right)$$

$$S_a\left(\frac{in}{\sec}\right) = \dot{\theta}(r\sin\theta)\left(1 + \frac{(\cos\theta)}{\sqrt{\left(\frac{\ell}{r}\right)^2 - (\sin\theta)^2}}\right) \tag{3-29}$$

Where, $\dot{\theta}$ is the crank-shaft angular velocity (rad/sec)

From the beater length ratio, the high speed of the beater at the beater free end (S_A) could be considered as revealed in equation 3-30 below:

$$\frac{\ell_1}{(\ell_1 + \ell_2)} = \frac{S_a}{S_A}$$

$$S_A\left(\frac{in}{\sec}\right) = S_a\left(\frac{(\ell_1 + \ell_2)}{\ell_1}\right) \tag{3-30}$$

Also, as shown in Figure 3-40, ϕ is the angular displacement of the shaking beater (radian). So, depending on the crank throw radius (3 inches), and position of the connection point between the shaking beater and turn buckle linkage (i.e., the input speed situation on the shaking beater), the beater angular displacement for the preliminary harvester design was equal to 15 degrees. The linear displacement at the beater free end ranged between 15 and 20 inches. For the final citrus harvester design, the shaking beaters penetrations into the grapefruit canopy, depending on the turn buckle length, are revealed in Table D-1.

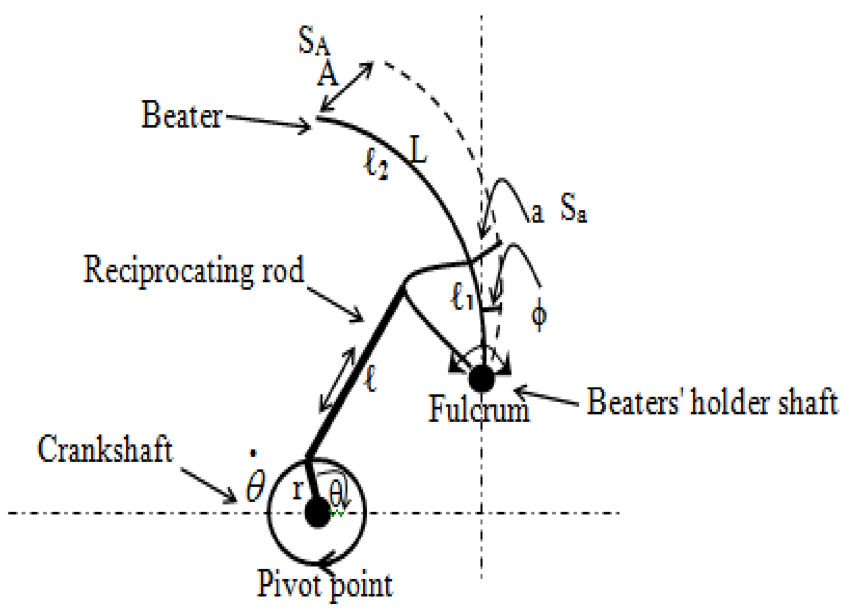

Figure 3-40. The shaking beater mechanism.

The Essential Field Measurements after the Harvesting Period

After the end-of-each harvesting (shaking) operation, the data that was collected included the required measurements of the number of detached fruits that released from the trees, and the number of fruits remaining on the trees which were snatched manually. Meanwhile, the damage to tree branches was visually evaluated. The numbers of the large citrus fruits, which were detached by the shakers, were counted manually, as shown in Figures 3-41 and 3-42. In addition, the numbers of the fruits left on the trees (unaffected by the canopy shaker) were enumerated separately.

Consequently, the percentages of the citrus fruits that are detached by each shaking operation (F_d) will be calculated mathematically by using the equation in the following format (Erdoğan et al., 2003):

Fruit detachment percentage, $$F_d(\%) = \left[\frac{N_d}{N_d+N_r}\right] \times 100 \qquad (3\text{-}31)$$

Where: N_d is the number of the most detached fruit (count), and N_r is the number of the fruit remaining on the citrus tree (count).

Thus, by knowing the total production of some citrus trees (detached and hanging fruit), the expected overall yield production of the citrus field per hectare (Y) can also be calculated by the following formula (Buyanov and Voronyuk, 1985):

Overall citrus fruit yield, $$Y\ \left(\frac{ton}{hectare}\right) = \frac{48.826 \times w_t}{a \times b} \qquad (3\text{-}32)$$

Where: w_t points to the absolute total fruit mass of each citrus tree separately (lb), a indicates the distance between the citrus trees lines (ft), and b indicates the distance between the citrus trees on each row (ft).

Likewise, if the tree damage has taken place during each shaking operation, the visible injuries to the tree's branches or limbs were assessed after each harvest operation.

Figure 3-41. Grapefruits on the ground after the harvest operation by the new canopy shaking machine (the preliminary design). [Photos courtesy of Naji Al-Dosary]

Figure 3-42. Grapefruits on the ground after the harvest operation by the final canopy shaking machine (final test) were calculated manually. [Photo courtesy of Naji Al-Dosary]

The Operational Economics of the Mechanical Citrus Harvester

Indeed, the citrus crops are the largest planted crops in the State of Florida. Florida had more than 6,000 citrus growers, planting almost 554,400 acres of all citrus varieties, producing about 129 million 90 lb boxes of fresh orange fruits, and 122.6 million 90 lb boxes of processed oranges through 475,900 acres during the 2006 season. Approximately 75 %, or more, of the United States orange crop is produced in the State of Florida. Thus, every season, 5,000 workers are hired for orchard care, and somewhere between 20 to 25 thousand laborers for fruit harvesting (Roka et al., 2009). Although the need for the number of laborers in the citrus fields has been reduced by using the mechanical harvesting approaches (e.g., the CCSC requires 6 laborers, while the TSC desires 3), the presence of a sufficient number of employees is still necessary during the harvest. Also, the fruit quality (fresh market fruit), requires the presence of hands to complete the following field operations: fruit picking, fruit removal and recovery, roadsiding, and hauling. Juice processing requires additional labor for: removing the plants debris that is transported by the harvest machine load, and the T-CS system also requires hands for gleaning the shaken fruit on the ground, late mature fruit detachment, and repair and replacement of field trees (Roka et al., 2009). Expenditures for manual harvesting have increased from 0.65 dollars per box (5.15 $/hr) in 2000 to 0.91 dollars per box (7.25 $/hr) in 2010, with the same labor’s productivity, which is estimated at eight boxes per hour. Mechanical harvesting offers a potential to substantial reduce harvesting costs. Based on cost and harvesting capacity data from existing citrus mechanical harvesting system, it is projected that if mechanical harvesting was fully adopted by juice orange growers, the cost of fruit harvesting could be lowered to 0.75 dollars per box (Roka, 2010).

Since the early 1950s, the citrus growers and the harvester manufacturing industries in Florida started to consider new approaches for citrus harvesting, particularly, a substitute for

manual harvesting. In late 1960s to early 1970s, mechanical citrus harvesting became a burning need, as the larger number of citrus acres demanded a larger labor force, that in turn increased the overall labor cost, which became difficult for the citrus growers to afford. Therefore, some citrus growers (e.g., 31,000 acres of orange plantings) shifted from the hand harvesting to the mechanical harvesting systems for the following reasons: the shift in emphasis of the citrus industries, who are dependent on efficient citrus harvesting, and some government sectors, toward the development of a new citrus harvesting technology to replace manual harvesting, and the increasing demand of the global market, especially for orange juice. For Florida citrus growers (i.e., as represented in Figure 3 by Roka et al., 2009), citrus production costs were lower than the costs of Florida harvesting (pick & roadside) between the seasons of 1994-95 and 2007-08. These results led some citrus growers (almost 7 %) to transition to mechanical harvesting. In the 2006-2007 growing season, production costs were increased due to the increase in costs of labor involved in harvesting and combating diseases (i.e., citrus greening (HLB) and canker). Mechanical harvesting helped both, by more efficient harvesting, and reducing the need for manual laborers in harvesting (i.e., reduce laborers practices that will reduce the likelihood of disease spread, which may be manually transferred between citrus trees). Furthermore, pesticide applications, and the replanting of citrus trees were estimated to increase the cost of the orchard care. Moreover, advancing technologies of citrus harvesting provided a chance for additional urban growth by enhancing the farmland values ($ 25,000/acre). By using any of the mechanical harvesting system (CCSC, T-CS, or TSC) with the abscission agent (CMNP), and the appropriate orchard design, labor productivity increased, and thus decreased the costs of citrus harvesting. Also, the mechanical harvesting reduced the number of the citrus laborers, so the risks associated with controlling labor and the cost of management were less. Finally, comparing the

performance of the three mechanical harvesting systems, TSC, CCSC, and T-CS, with the manual harvesting for the Hamlin and Valencia blocks, found that the number of trees that were harvested in an hour by these systems was recorded as 190-229, 361-466, and 184-298 respectively, while the laborers harvested 2 to 4 trees per hour. Also, the laborers productivity with the mechanical harvesting systems was assumed to be 76-96, 103-122, and 16-20 (box/hr) respectively, in contrast to laborers productivity without the mechanical harvesting techniques which was estimated at about 8 to 12 (box/hr) (Roka et al., 2009). The harvesting costs ($/hr) were assumed to be affected by field operations such as, the type of harvesting machine system (TSC, CCSC, or T-CS), tree design (e.g., skirting, pruning, and hedging) ($/acre), chemical applications (i.e., CMNP) ($/acre), the amount of fruit detachment ($/hr), fruit recovery ($/box), fruit picking and hauling ($/box or goat), fruit gleaning ($/box), tree repair and replacement, repair to the irrigation system ($/hr) and the fixed costs (i.e., depreciation cost, interest payment, taxes, or insurance cost) ($/box or yearly yield). Generally, the lower harvest cost is an important economic objective for a new mechanical harvester design (Roka, 2008 and Roka et al., 2009).

Accordingly, the effect of each shift in the anticipated economic variables' on the overall cost of harvesting is presented in Table 3-4 (Roka et al., 2009).

Table 3-4. The results of the impact of the anticipated economic variables' on harvesting costs. [Adapted from Roka et al., 2009]

No.	Anticipated economic variables	The harvesting cost effect
1	The type of harvesting machine system	The mechanical harvesting assumes to save more than 50 % of the harvesting cost where CCSC needs 6 labors and TSC requires 3 labors, while manual harvesting needs 20- 25,000 labors, and an increase the harvesting speed (184- 466 tree/hr).
2	Fruit detachment	Raising the fruit detachment up to 90-95 %.
3	Fruit recovery	Raising the fruit recovery up to 87-99 % will reduce the gleaning cost.
4	Fruit picking, roadsiding, and hauling	Different harvesting machines manufactured according to the situation of the orchard design, where one type requires a team of workers to accumulate the fruits on the surface, while the other machines allow the citrus fruit to fall on a suitable fruit interception surface for collecting and transporting to the truck out of the field. So that will affect the harvesting cost.
5	Fruit gleaning	Mechanical harvesting cost with gleaning estimate to 1.25 dollar per box, while 1 dollar per box without gleaning.
6	conveying debris	The debris that is included during the fruit loads will increase the transportation cost and raises the haul cost.
7	Trees design (skirting, pruning, and hedging)	Will decrease the tree damages, increase the harvesting machines performance, and will defined the proper mechanical harvesting system.
8	Damage on the citrus trees, irrigation system, and trees repair and replacement	The damage on the citrus trees and irrigation system will not let the citrus grower allow mechanical harvesting since the repair and replacement costs will increase.
9	Chemical applications (CMNP)	By joining the CMNP application with the mechanical harvesting system, the harvesting cost will be reduced, increase the fruit yields’, and 50 % of the fruit detachment force is reduced. Also, 50 % of the field’s yield (fruiting trees) is reduced by neglecting removal of the late ripe and immature fruits from the trees twigs so the CMNP application will help to remove the late ripe and immature fruits during the harvesting time.
10	The fixed costs	Depreciation cost, interest payment, taxes, or insurance cost should be considered throughout the harvesting cost calculation.

Subsequently, the overall operations cost (Hc, \$/hr) of the mechanical harvesting of the new citrus fruits harvester and two trucks can be determined by using the calculation of the following equation of cost with the coefficients in Tables 3-5 and 3-6 (El-Gindy et al., 2009):

$$Hc = \frac{P_M}{Y_H}\left(\frac{1}{M_L} + \frac{R_i}{2} + R_t + R_{rm}\right) + \left(L_f \; P_w \, F_p \, F_{cns}\right) + \frac{L_{ms}}{O_{mo}} \tag{3-33}$$

Where, Hc is the gross cost of the mechanical harvesting by the machine (\$/hr), P_M is the price of the mechanical harvester (\$), Y_H is the predicted yearly operation hours (hr/year), M_L is the life-expectancy of the mechanical harvester (year), R_i is the rate of interest (%/year, 8 % of the harvester price/year, Hunt, 1977), R_t is the rate of tax (%/year), R_{rm} is the rate of the mechanical harvester maintenance (%), L_f is the lubrications factor (i.e., that is estimated equal to 0.90), P_w is the machine power (kw), F_p is the price of fuel (\$/gal), F_{cns} is the consumption of fuel (gal/kw.hr), L_{ms} is the labor monthly salary (\$, expected as 10.90 \$/hr, USDA, 2011), and O_{mo} is the predicted average of the operation hours for each month (i.e., it is anticipated equal to 145.50 hour/month).

As a final point, by laying the proposed values of the parameters cost, as shown in Tables 3-5 and 3-6 below, in the former equation of cost 3-33, the gross cost of the new prototype harvester operation (\$/hour) will be prominently identified (Muraro, 2012, and Hunt, 1977).

Table 3-5. Estimated operating expense of the new self-propelled citrus harvester with its trucks for the harvest season 2013-14.

Coefficients of the Mechanical Harvesting Cost by the New Citrus Harvester	
Classification	Cost
Expected purchase price ($)	250,000[1]
Life-expectancy (years)	10.00[2]
Yearly operation hours (hr/year)	873[3]
Power Hp (kw)	51.40 (38.3) (for two engines)
Maintenance cost ($/hr)	57.27[1] (25,000 $/season)
Rate of interest (%)	8.00[4]
Insurance rate ($/year)	0.25 % of purchase price[4]
Local rate of tax (%)	6.25
Local price of fuel ($/gal)	3.85
Estimated consumption of fuel (gal/kw hr)	0.016
Local price of oil ($/hr)	0.98 (5.99 $/1quart)
From prior equation 3-33	Gross cost of mechanical harvesting by the new machine *Hc* ($/hr), 152.38, include truck operating cost

Table 3-6. Average operating expenses of the grapefruit manual harvesting.

Coefficients of the Manual Harvesting Cost	
Operation Type	Cost ($/box)
Grapefruit picking	0.71[5]
Grapefruit roadsiding	0.95[5]
Total cost of manual harvesting	1.66

[1]estimated cost based on similar machine; [2]estimated machine life; [3]estimated yearly hour based on similar machine; [4]Hunt, 1977; and [5]Muraro, 2012.

Method of Statistical Analysis of the Experiments Data

Practically, the field trials for the preliminary canopy shaker design include the following three typical operating variables:

1- Two forward speeds (ground speeds) of the canopy shaker.

2- Three rotational speeds of the shaking beaters (i.e., three rotational speeds of the motors that are driving the beaters' shafts via the crank-shafts).

3- Two different scales of the shaker stroke displacement (i.e., either the harvester tunnel width or the shaking beaters position).

The statistical test design, within the citrus field of the PSREC, used completely randomized design method (C.R.D.). The effect of all the variables (i.e., two forward speeds of the shaker machine, three rotational speeds of the shaking beaters (shaking speeds), and three positions of the shakers) on the amount of the removed fruits and the limbs injuries were analyzed to evaluate the performance of the citrus canopy shaking machine. Thus, there will be 12 coefficients ($2 \times 3 \times 2$) in total. The procedure of measurement was replicated three times on three different trees with a constant set of coefficients to achieve precise results. Consequently, to accomplish this statistical design, 36 random citrus trees (one tree for each experimental unit) are desired. The distribution method of these coefficients in the citrus field experiments was not discriminated. ANOVA, an analysis of variance use the General Linear Model (GLM. or GLIMMIX) through the pack of SAS, the statistical analysis software (SAS Institute Inc., 2012) at 90 % of the level of significance (p=0.10) will be considered. Typically, SAS is applied to make a decision about the contributive parameters that could have a significant effect on the canopy shaker performance for the citrus fruit detachment and tree injuries. Simultaneously, the less significant difference method (L.S.D.) will be utilized to know the differences between the means of these coefficients and the effect of the interaction between the operating variables, in order to determine the most influential factors on both the performance of the harvesting

machine as well on the other operating variables. Moreover, the interaction between the operating variables can be publicized within the following distinctive domains:

1- The effect of the forward speeds (ground speeds, mph) of the canopy shaker.

2- The effect of rotational speeds of the beaters (shaking speeds, inch/sec).

3- The effect of the shakers displacements (harvester tunnel width, inch).

4- The effect of interaction between the forward speeds of the canopy shaker and rotational speeds of the shaking beaters.

5- The effect of interaction between the forward speeds of the canopy shaker and the harvester tunnel width.

6- The effect of interaction between the rotational speeds of the shaking beaters and the harvester tunnel width.

7- The effect of the interaction between the forward speeds of the canopy shaker, the rotational speeds of the beaters, and the harvester tunnel width (shaking beaters positions).

Therefore, the previous equations 3-29 and 3-30 were used to determine the shaking speeds of the harvester's beaters (linear speed) at the input point, which is the connecting point between the beater and the turn buckle link, and the output shaking speed at the end point of the beater (maximum shaking speed), depending on the rotational speed of the crank-shaft that was measured by using the tachometer. Consequently, the combination of the citrus field experiments were included the following variables as shown in Table 3-7.

Table 3-7. Operating variables that were used for the preliminary citrus harvesting machine's experiments in the summer harvest of 2013.

Series		Crank-Shaft Speed $\dot{\theta}$ (rpm)	Input Beaters Speed S_a (inch/sec)	Output Speed at the Free End of the Beater S_A (inch/sec)	Harvester Forward Speed (mi/hr)	Machine Internal Tunnel Width (inch)
1		124.40	40	91.43	0.90	69
2		176.80	56	128	1.20	75
3		229.20	73	166.87	-----	---
						Turn Buckle Length (inch)
Acceleration	1	144.10	45.30	103.54		10
Trials	2	209.54	65.90	150.63		11
	3	--------	-------	--------		12

For the harvest of winter-2014, the field trials for the harvest efficiency of the final canopy shaker design (final test) included the following three typical operating variables:

1- Two forward speeds (ground speeds) of the canopy shaker.

2- Two rotational speeds of the shaking beaters (i.e., two rotational speeds of the motors that are driving the beaters' shafts via the crank-shafts).

3- Three different scales of the shaker stroke displacement (positions of the shaking beaters, i.e., three different turn buckle lengths).

As was previously done for the statistical test design and data analysis within the field experiments of the preliminary harvester design in the late summer harvest of 2013, the same examinations were accomplished by using 12 coefficients (2 × 2 × 3) in total for the final harvester design performance test in the winter harvest of 2014, as shown in Table 3-8. The performance measurement procedures were replicated five times on five different trees with constant set of the coefficients to achieve precise results. Consequently, to accomplish the statistical design of the field experiments of the final citrus harvester design, 60 random grapefruit trees (one tree for each experimental unit) were utilized. The combination of the citrus field experiments included the following variables, as shown in Table 3-9.

Table 3-8. Statistical design of the operating variables test that were used for the final citrus harvesting machine's experiments in the winter of 2014.

Operating Variables	The Grapefruit Orchard Lines Line 1	 Line 2	 Line 3	Harvest Direction
Machine Forward Speeds Beaters Shaking Speeds (Knob turn number of the flow control valve) Beaters Positions (Turn buckle length, inch)	Fast Forward Speed Lowest Shaking Speed-2.5 16	Fast Forward Speed Highest Shaking Speed-3 12	Fast Forward Speed Lowest Shaking Speed-2.5 Default position	North ↑
	Slow Forward Speed Lowest Shaking Speed-2.5 16	Slow Forward Speed Highest Shaking Speed-3 12	Slow Forward Speed Lowest Shaking Speed-2.5 Default position	
	Fast Forward Speed Highest Shaking Speed-3 16	Fast Forward Speed Lowest Shaking Speed-2.5 12	Fast Forward Speed Highest Shaking Speed-3 Default position	
	Slow Forward Speed Highest Shaking Speed-3 16	Slow Forward Speed Lowest Shaking Speed-2.5 12	Slow Forward Speed Highest Shaking Speed-3 Default position	South

* Each treatment (12 treatments) was replicated five times on five different trees.

Table 3-9. Operating variables that were used for the final citrus harvesting machine's experiments in the winter of 2014.

Series	Crank-Shaft Speed $\dot{\theta}$ (rpm)	Input Beaters Speed S_a (inch/sec)	Output Speed at the Free End of the Beater S_A (inch/sec)	Harvester Forward Speed (mi/hr)	Turn Buckle Length (inch)
1	178.98	56.50	131.02	0.62	12
2	230.00	73.00	167.80	1.42	Default Position*
3	-----	-----	-----	-----	16
					Turn Buckle Length (inch)
Acceleration Trials 1	202.00	63.74	147.87		12

* Beaters default position refers to setting the first beater on top for each unit with turn buckle length of 15 inches, the second beater on top set with turn buckle length of 14 inches, and the next 5 beaters down set with turn buckle length of 12 inches.

CHAPTER 4
RESULTS AND DISCUSSION

Effect of the New Canopy Shaking Machine on Citrus Harvesting

Practical experiments of the new prototype of the citrus harvester were carried out at the Plant Science Research and Education Center in Citra (PSREC), which is located 20 miles southeast of the city of Gainesville. In this study, the operational effectiveness of the preliminary prototype of the citrus harvesting machine was done to investigate the effects of certain operating variables, such as the harvester's velocity (i.e., 0.90 and 1.20 mi/hr), harvesting tunnel's width (i.e., 69 and 75 inches), and the shakers' shaking speed (i.e., 40, 56, and 73 inch/sec), on the fruit dislodgement rate (harvester efficiency), and the distribution of the acceleration magnitude (g) on the grapefruit tree canopy. Also, the improved effectiveness of the final design modifications were investigated to determine the effects on certain operating variables, such as the harvester's velocity (i.e., 0.62 and 1.42 mi/hr were the average low and high forward speeds of the harvester machine), harvester's beaters position (i.e., turn buckles length at default position, 12, and 16 inches), and the shaking speed (i.e., 56.50, and 73 inch/sec) on the fruit dislodgement rate (harvester efficiency). The distribution of the acceleration magnitude (g) in the grapefruit tree canopy at a harvester tunnel width of 69 inches was also investigated. The harvester's beaters default position was set as follows; the first beater from top had a turn buckle length of 15 inches, the second beater from top had a turn buckle length of 14 inches, and the next 5 beaters tapered down to a turn buckle length of 12 inches. The obtained harvesting data has been analyzed statistically, using statistical analysis software (SAS), at 90 % level of significance, to distinguish the most important operational variables of the new prototype harvester, and to determine whether there is any significant interaction among them. The results have been presented below:

Final Results of the Preliminary Harvesting Machine Design

Effect of the Harvesting Machine Forward Speeds on the Field Harvesting

Table 4-1 shows the effects of forward speeds of the preliminary harvester machine on the amount of grapefruits dropped from the tree canopies. In general, machine forward speed affects the time for shaking trees canopies, where increasing the harvester forward speed decreases canopy shaking time, and shaking time increased with low forward speeds. From the field trials, it was found that the shaking time for the highest forward speed (1.20 mi/hr) was almost 4.30 sec/tree, while the shaking time for the lowest forward speed (0.90 mi/hr) was almost 6.49 sec/tree. It was found that the average amount of detached grapefruit decreased at the highest forward speed (1.20 mi/hr). When the forward speed increased, the highest speed gave the lowest average of detached grapefruit (11 fruits/tree). The average amount of grapefruits ranged between 11 fruits/tree for the second forward speed (1.20 mi/hr) and 21 fruits/tree for the first speed (0.90 mi/hr), so the average amount of detached fruit is decreased by increasing the harvester forward speed. Thus, by applying the statistical analysis to the field data, it was found that, at the 10 % level of significance, there is an obvious significant difference between the influence of the low and high speed in this study on the amount of detached grapefruits. Also, Table 4-2 shows that there is no significant difference, at the 10 % level of significance, for the influence of the harvesting machine forward speeds on the amount of attached fruits on the grapefruit trees. As observed, by increasing the forward speed, the average amounts of the attached grapefruits on the trees were decreased. The amount of attached fruits ranged from 57 fruits/tree for the speed 0.90 mi/hr to 55 fruits/tree for the highest speed 1.20 mi/hr. Meanwhile, influence of the harvester forward speeds on the fruit detachment percentage is shown in Table 4-3. The table shows that by increasing the harvester’s forward speed from 0.90 mi/hr to 1.20 mi/hr, the percentage of the detached grapefruits will be decreased from 29.54

% to 18.71 %, respectively. From the resulting analysis, it was found that, statistically, there is a clear significant difference, at the 10 % level of significance, of the harvesting machine forward speeds influence on the grapefruit detachment percentages, which were extracted out of the tree canopies.

Table 4-1. The average of the detached fruit (fruits/tree).

	Forward Speed of the Harvester (mi/hr)	
	0.90	1.20
Symbol	Mfd1	Mfd2
Ave. *	21 [a]	11 [b]
S.D.	15.17	8.72

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Table 4-2. The average of the adhered fruit on the trees (fruits/tree).

	Forward Speed of the Harvester (mi/hr)	
	0.90	1.20
Symbol	Mfd1	Mfd2
Ave. *	57 [a]	55 [a]
S.D.	30.88	44.01

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Table 4-3. The average of the fruits detachment percentage (%).

	Forward Speed of the Harvester (mi/hr)	
	0.90	1.20
Symbol	Mfd1	Mfd2
Ave. *	29.54 [a]	18.71 [b]
S.D.	14.94	11.84

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Effect of the Harvesting Machine Tunnel Widths on the Field Harvesting

The results of the adjustable machine tunnel widths influence on the amount of the detached fruit are shown in Table 4-4. Numerically, the tunnel width of 69 inches reveals a high amount of detached grapefruits (18 fruits/tree), while the large tunnel width (75 inches) gives 16 fruits/tree of detached grapefruits. As has been observed, by increasing the machine tunnel width, the amount of detached fruits will be decreased, but there were no significant differences, at the level of 10 % significance, of the effect of the tunnel width at 69 inches and tunnel width at 75 inches on the average of the detachment quantity of the grapefruits. The reason for that maybe the machine was working at tunnel width greater than the lateral width of the tree canopy in the field, or the large tunnel width did not provide enough penetration for the machine beaters, which decreased the amount of detached fruits. Furthermore, Table 4-5 shows the effect of the harvesting tunnel widths on the average amount of grapefruits remaining on the trees. The results reveal that by increasing the harvester tunnel width from 69 inches to 75 inches, the average amount of the fruit remaining on the tree canopies will be increased from 45 fruits/tree to 67 fruits/tree, respectively. Therefore, there was an increase in the amount of fruit remaining on the tree canopies by increase of the machine tunnel width. Statistical analysis found there were no significant differences between the effect of the harvester tunnel width at 69 inches and the extended width at 75 inches on the average amount of attached grapefruits on tree canopies, at the 10 % level of significance. In addition, data in Table 4-6 illustrates the influence of the harvester tunnel width on the average of the fruits detachment percentage (%). As shown in Table 4-6, the fruit detachment percentage is decreased by increasing the machine tunnel width from 69 inches to 75 inches. In other words, increasing the harvester tunnel width from 69 inches to 75 inches, leads to decrease in the percentage of fruit detachment from 27.31 % to 23.64 %. According to the statistical analysis, by the 10 % level of significance, it was found that, there

was no significant difference between the effectiveness of the two harvester tunnel widths on the fruits detachment percentage.

Table 4-4. The average of the detached fruit (fruits/tree).

	Tunnel Width of the Harvester (in)	
	69	75
Symbol	Tw1	Tw2
Ave. *	18[a]	16[a]
S.D.	18.93	6.76

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Table 4-5. The average of the adhered fruit on the trees (fruits/tree).

	Tunnel Width of the Harvester (in)	
	69	75
Symbol	Tw1	Tw2
Ave. *	45[a]	67[a]
S.D.	31.07	37.12

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Table 4-6. The average of the fruits detachment percentage (%).

	Tunnel Width of the Harvester (in)	
	69	75
Symbol	Tw1	Tw2
Ave. *	27.31[a]	23.64[a]
S.D.	15.56	14.02

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Effect of the Shaking Speeds of the Harvester Beaters on the Field Harvesting

In terms of the machine beater frequency, Table 4-7 shows the influence of diverse levels of the machine beaters speeds (beaters vibrations) on the average amount of the detached grapefruit (fruits/tree). When the beaters' shaking speed is increased from 40 in/sec to 56 in/sec, the average amount of detached fruits increased from 10 fruits/tree to 28 fruits/tree, while the fruits quantity decreased at the highest beaters speed 73 in/sec to 12 fruits/tree. Unexpectedly, field observations indicated that at beaters shaking speed of 73 in/sec, the rotational speed of the left crank-shaft was unstable, as the beaters engaged with some sturdy tree branches, especially ones with significant heavy limb structure and lots of cramped crotch angles. Thus the tree canopy and limb size, crotch density, and the tree yields may have led to the difference of the amount of grapefruit detached or left on the tree canopies. From the statistical analysis, at the 10 % level of significance, it was found that, there is no significant difference between the influence of the beaters speeds 73 in/sec and 40 in/sec on the average amount of the detached fruit, but there is a significant difference between the influence of the second shaking speed 56 in/sec, and both the low (40 in/sec), and high (73 in/sec) shaking speed on the amount of detached fruit. On the other hand, where the number of detached fruit was lower, the amount of attached fruit left on trees was higher, as shown in Table 4-8. In general, when the beaters shaking speed is increased from 56 in/sec to 73 in/sec, the actual average amount of fruits remaining on the tree canopies decreased from 80 fruits/tree to 22 fruits/tree, while increasing the shaking speed of beaters from 40 in/sec to 56 in/sec led to an increase in the average amount of attached fruits remaining on the grapefruit trees from 56 fruits/tree to 80 fruits/tree. According to visible differentiations between the averages of the attached fruits for the shaking speed 40 in/sec and 73 in/sec, as well as between 40 in/sec and 56 in/sec, and also between the speed 56 in/sec and 73 in/sec, it was found that statistically, there is a significant difference between the second beaters

speed 56 in/sec and third shaking speed 73 in/sec. On the contrary, there are no significant differences between the first shaking speed 40 in/sec and second speed 56 in/sec, or between the first beaters speed 40 in/sec and the third shaking speed 73 in/sec in terms of the average amount of the attached grapefruits (at the 10 % level of significance). In addition, Table 4-9 shows the effect of diversity in the harvester beaters speed on the proportion of the average detachment of the grapefruits. It is obvious that with increase in the harvester beaters' speed from 40 in/sec to 73 in/sec, the grapefruit detachment rate will be increased from 17.90 % to 35.77 %. Ostensibly, there are effective differences between the beaters shaking speeds, so accordingly, the statistical analysis found there are significant differences between the effects of the machine beaters speeds on the average of the fruits detachment percentage, at the level of significance 10 %. In other words, that means there are significant differences between the lowest beaters shaking speed 40 in/sec and the highest beaters shaking speed 73 in/sec, as well between first speed 40 in/sec and the second 56 in/sec, and also between the second beaters shaking speed 56 in/sec and the third beaters speed 73 in/sec in terms of the average amount of the grapefruits detachment percentage (at the 10 % significance level).

Table 4-7. The average of the detached fruit (fruits/tree).

	Beaters Shaking Speed (inch/sec)		
	40	56	73
Symbol	Shs1	Shs2	Shs3
Ave. *	10 [b]	28 [a]	12 [b]
S.D.	6.79	17.18	4.89

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Table 4-8. The average of the adhered fruit on the trees (fruits/tree).

	Beaters Shaking Speed (inch/sec)		
	40	56	73
Symbol	Shs1	Shs2	Shs3
Ave. *	56 [cd]	80 [ac]	22 [bd]
S.D.	31.02	33.26	5.01

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Table 4-9. The average of the grapefruit detachment percentage (%).

	Beaters Shaking Speed (inch/sec)		
	40	56	73
Symbol	Shs1	Shs2	Shs3
Ave. *	17.90 [c]	26.20 [b]	35.77 [a]
S.D.	16.59	12.38	8.01

* Averages, which have been followed by the same letter in the row, do not have a significant difference statistically at a 0.90 confidence level.

Effect of the Interaction between the Machine Forward Speeds and its Tunnel Widths on the Field Harvesting

Table 4-10 illustrates the effect of interaction between the forward speeds of the harvesting machine with the harvesting tunnel widths on the amount of the detached grapefruit. From this interaction, it was found that the highest average amount of detached fruits was equal to 30 fruits/tree, caused by interaction between the forward speed 0.90 mi/hr and tunnel width 69 inches, while the lowest amount of detached fruits were 6 fruits/tree, as a result of the interaction between the forward speed 1.20 mi/hr and harvesting width of 69 inches. Also, by setting up the statistical analysis for this interaction effect, it was found that the interaction of the ground speed 0.90 mi/hr and the harvester tunnel width 69 inches on one side, and the interaction between the ground speed 0.90 mi/hr and tunnel width 75 inches; second ground speed 1.20 mi/hr and tunnel width 75 inches; and second ground speed 1.20 mi/hr and tunnel width 69 inches all on the other side, is considered as a clear significant influencer on the detached fruit amount at 90 % level of confidence. Also, the results do not show significant differences on the amount of detached grapefruit under the influence of the other interactions, also at 90 % level of confidence. The average amount of the attached fruits on the tree canopies, due to the interaction of the machine forward speeds and its harvesting tunnel widths, are shown in Table 4-11. By this interaction, the average remaining fruits on the trees ranged between 34 fruits/tree, which was gained by interaction of the harvester speed 1.20 mi/hr and 69 inches internal width, and 97 fruits/tree, which was gained by the interaction of the forward speed 1.20 mi/hr and the tunnel width 75 inches. The highest average amount of the fruit remaining on the grapefruit tree (97 fruits/tree) occurs due to the interaction between the machine forward speed 1.20 mi/hr and tunnel width 75 inches, when compared with other interactions. As a result of this interaction, the precise statistical analysis found that the effect of the interaction between diverse machine forward

speeds, and its tunnel widths, on the attached grapefruits amount, is generally assumed as a non-significant factor, and does not have comparison significance, at the 90 % confidence level. Furthermore, from the relative relationship between the detached fruit amount and the amount of the fruit that remained on grapefruit trees, the fruit detachment percentage, is shown in Table 4-12. Table 4-12 also shows the actual results of the interaction between the harvester ground speeds, and its tunnel widths, on the average grapefruit detachment percentage. Also, as can be seen from Table 4-12, the highest average percentage of the fruit detachment was 36.10 % as a result of interaction between the harvester tunnel width 69 inches and the lowest ground speed 0.90 mi/hr, while the interaction between the internal tunnel width of 69 inches and the highest ground speed 1.20 mi/hr resulted in the lowest percentage of the fruit detachment, 18.53 %. From the data results, by increasing the speed from 0.90 mi/hr to 1.20 mi/hr with the tunnel width 75 inches, the fruit detachment percentage will be decreased, and likewise, the detachment percentage will decreased by increasing the machine forward speed with the width also set at 69 inches. On the other hand, by decreasing the machine internal tunnel width from 75 to 69 inches, with a constant ground speed 0.90 mi/hr, the average fruit detachment percentage will be increased to 36.10 %, and at the forward speed 1.20 mi/hr, the fruit detachment percentage will increase from 18.53 % to 19.07 % by increasing the harvesting width from 69 to 75 inches. Statistically, it is clear that the interaction influence of the harvester tunnel width 69 inches and ground speed of the harvester 0.90 mi/hr on one side, and the interactions between the first harvester ground speed 0.90 mi/hr and its tunnel width 75 inches; harvester speed 1.20 mi/hr and harvesting tunnel width 75 inches; and the ground speed 1.20 mi/hr and tunnel width 69 inches all on the other side, recorded clearly as having high significant differences on the fruit

detachment percentage. The other interactions were overall recorded as not having significant effects on each other on the proportion of the detached fruit, at the 10 % level of significance.

Table 4-10. The average amount of the detached fruit (fruits/tree).

Tunnel Width (in)	Harvester Forward Speed (mi/hr)		Ave.
	0.90	1.20	
75	15[b]	20[b]	16
69	30[a]	6[b]	18
Ave.	21	11	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-11. The average of the adhered fruit on the trees (fruits/tree).

Tunnel Width (in)	Harvester Forward Speed (mi/hr)		Ave.
	0.90	1.20	
75	57[a]	97[a]	67
69	55[a]	34[a]	45
Ave.	57	55	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-12. The average of the grapefruit detachment percentage (%).

Tunnel Width (in)	Harvester Forward Speed (mi/hr)		Ave.
	0.90	1.20	
75	25.17[b]	19.07[b]	23.64
69	36.10[a]	18.53[b]	27.31
Ave.	29.54	18.71	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of the Interaction between the Beaters' Shaking Speeds and the Machine Tunnel Widths on the Field Harvesting

Influence of the interaction between internal tunnel widths and beaters shaking speeds of the citrus harvester on the amount of the detached grapefruit is shown in Table 4-13. As can be distinguished in Table 4-13, with the specific harvester beaters' speed 56 in/sec, the amount of detached fruits will be decreased by increasing the harvester's tunnel width, but the detached grapefruit amount at the highest shaking speed 73 in/sec, and the lowest shaking speed 40 in/sec will increase by increasing the internal width of the harvesting tunnel. Moreover, for both tunnel widths 69 inches and 75 inches, the amount of the detached fruits increased by increasing the beaters' shaking speed from 40 in/sec to 56 in/sec, but the amount of detached fruit decreased at the highest shaking speed of 73 in/sec. The average amount of detached fruit ranged between 8 fruits/tree as a minimum average due to the interaction of the tunnel width of 69 inches and beaters' shaking speed of 73 in/sec, and 47 fruits/tree as a maximum average which resulted from the interaction of beaters' shaking speed 56 in/sec and harvesting width 69 inches. Statistical analysis found that the effect of the interaction between the harvesting tunnel width 69 inches and the harvester beaters shaking speed 56 in/sec on one side, and the interactions between the other beaters' shaking speeds and harvester's internal tunnel widths on the other side, is recorded as having a high statistically significance on the amount of detached grapefruits at 0.10 level of significance. In contrast, the other interactions between other beaters' shaking speeds and the harvesting tunnel widths had no statistically significant effect on the amount of detached grapefruits on each other at a level of significance 10 %.

For the grapefruits remaining on the tree canopies, the results in Table 4-14 pointed out the impact of the interactions between the harvester beaters' shaking speeds and its internal tunnel widths on the average amount of fruit that remained on the canopies. The highest average

amount of fruit remaining on the tree canopies was 85 fruits/tree, as a result of the interaction between the shaking speed 40 in/sec and tunnel width 75 inches. This recognizable amount of fruits resulted from the fact that the beaters' penetration into the canopies was not sufficient to shake the whole tree canopy synchronously with the lowest shaking speed 40 in/sec. Also, the minimum average amount of the attached fruit was 19 fruits/tree, based upon the interaction between the tunnel width 69 inches and the beaters' shaking speed 73 in/sec. This average amount of fruit is obtained since the beaters' penetration into the tree canopies was reasonable enough to shake it fully with the highest shaking speed 73 in/sec. Also, it can be observed from Table 4-14 that by increasing the shaking speed from 40 in/sec to 73 in/sec with the highest internal tunnel width 75 inches, the average amount of fruits remaining on the tree canopies is decreased from 85 fruits/tree to 24 fruits/tree. However, at the tunnel width 69 inches, increasing the shaking speed from 40 in/sec to 56 in/sec increased the grapefruits remaining on the canopies, but the highest beaters shaking speed 73 in/sec, resulted in the lowest average amount of grapefruit remaining on tree canopies (19 fruits/tree). From the statistical analysis results of the obtained data, it was found clearly that the interaction effect between the beaters' shaking speed 73 in/sec and tunnel width 69 inches on one side, and the interactions between the beaters' shaking speed 40 in/sec and tunnel width 75 inches; shaking speed 56 in/sec and tunnel width 69 inches; and the shaking speed 56 in/sec and tunnel width 75 inches, all on the other side, recorded as having a high significant difference on the amount of grapefruits remaining on the tree canopies, at the 10 % level of significance. Also, there were significant differences for the effect of the interactions between the beaters' shaking speed 40 in/sec and the tunnel width 75 inches on one side, and the interactions between the harvester beaters' shaking speed 73 in/sec and tunnel width 75 inches; and the beaters' shaking speed 40 in/sec and tunnel width 69 inches

on the other side, on the amount of grapefruits remaining on the tree canopies, at level of significance 10 %. No further significant differences were found between the effect of the other beaters shaking speeds and the harvesting tunnel widths interactions on each other, regarding amount of fruit remaining on the tree canopies, at 10 % the level of significance.

In addition, Table 4-15 refers to the influence of the interaction between the harvester's internal tunnel widths and the beaters' shaking speeds on the grapefruit detachment percentage. From the results of the shaking speed and harvesting width interaction, the maximum detachment percentage was 41.58 % using the interaction of 75 inches tunnel width and 73 in/sec of the beaters' shaking speed, while the minimum percentage was 12.45 % resulting from the interaction between the shaking speed 40 in/sec and tunnel width 75 inches. Also as observed, the detachment percentage of the grapefruit is increased from 12.45 % to 41.58 % by increasing the shaking speed from 40 in/sec to the highest beaters speed 73 in/sec at the highest tunnel width 75 inches. At the tunnel width 69 inches, the fruit detachment percentage is increased from 20.63 % to 38.05 % by increasing the shaking speed from 40 in/sec to 56 in/sec, while the fruit percentage decreased to 29.95 % at the shaking speed 73 in/sec. This decline at the high shaking speed may have been due to the shaker motor stalling on heavy limb structure. On the other hand, at the shaking speeds 40 in/sec and 56 in/sec, the fruit detachment percentage increased by decreasing the harvester's tunnel width from 75 to 69 inches, but at the beaters' shaking speed 73 in/sec, the fruit detachment percentage is increased from 29.95 % to 41.58 % by increasing the tunnel width from the default width 69 to 75 inches. Statistically, it is clear that, the interaction influence between the harvester's tunnel width 75 inches and the lowest beaters' shaking speed 40 in/sec on one side, and the harvester's tunnel width 75 inches with the highest beaters' shaking speed 73 in/sec; and the default harvester's tunnel width 69 inches with the highest

beaters’ shaking speed 73 in/sec, all on the other side, recorded as having significant differences at the level of significance 10 % on the fruit detachment percentage. Also, from the statistical analysis, it was clear that there are no significant differences due to effect of the interactions between the other harvester tunnel widths and the beaters shaking speeds on each other, at the level of confidence 90 %, on the proportion of the detached grapefruits. In conclusion, should be noted that for both tunnel widths 75 and 69 inches, in increasing the shaker speed from 40 in/sec to 56 in/sec has a favorable interaction of grapefruit detachment percentage, but the maximum grapefruit detachment percentage (41.58 %) had achieved by interaction of tunnel width 75 inches and shaker speed 73 in/sec.

Table 4-13. The average of the detached fruit (fruits/tree).

Tunnel Width (in)	Beaters Shaking Speed (inch/sec)			Ave.
	40	56	73	
75	12[b]	18[b]	17[b]	16
69	9[b]	47[a]	8[b]	18
Ave.	10	28	12	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-14. The average of the adhered fruit on the trees (fruits/tree).

Tunnel Width (in)	Beaters Shaking Speed (inch/sec)			Ave.
	40	56	73	
75	85[a]	81[ac]	24[bc]	67
69	41[bc]	78[ac]	19[b]	45
Ave.	56	80	22	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-15. The average of the grapefruit detachment percentage (%).

Tunnel Width (in)	Beaters Shaking Speed (inch/sec)			Ave.
	40	56	73	
75	12.45[bc]	20.27[ac]	41.58[a]	23.64
69	20.63[ac]	38.05[ac]	29.95[a]	27.31
Ave.	17.90	26.20	35.77	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of the Interaction between the Beaters' Shaking Speeds and the Machine Forward Speeds on the Field Harvesting

The data in Table 4-16 describe influence of the interaction between forward speeds of the harvesting machine with its beaters' shaking speeds on the amount of the detached fruits. The average amount of the detached fruit ranged between the minimum of 3 fruits/tree, which resulted from the interaction of the highest forward speed 1.20 mi/hr with the lowest beaters' shaking speed 40 in/sec, and the maximum amount of 31 fruits/tree due to the interaction of machine forward speed 0.90 mi/hr and shaking speed 56 in/sec. The lowest average amount of the detached fruit 3 fruits/tree occurred at the highest forward speed 1.20 mi/hr, which does not furnish enough time to shake the whole tree canopy (4.30 sec/tree) when also operating at the lowest shaking speed 40 in/sec. The highest average amount of detached fruit (31 fruits/tree) was obtained at the lowest forward speed (0.90 mi/hr), which may have furnished enough time (6.49 sec/tree) to shake the whole tree canopy. Also, from the table it can be observed that at harvester beaters shaking speeds of 40 in/sec, 56 in/sec, and 73 in/sec, the detached fruit amounts are decreased by increasing the harvester forward speed from 0.90 mi/hr to 1.20 mi/hr. Similarly, at both harvester forward speeds 0.90 mi/hr and 1.20 mi/hr, increasing the beaters shaking speed from 56 in/sec to 73 in/sec, decreased the detached fruit amounts. This may be due to decreased shaker torque at highest motor RPM. It is clear that the maximum average amount of the detached fruits occurred at a shaker speed of 56 in/sec for both forward speeds. From the statistical analysis, it was found that, the interaction effect between the harvester's forward speeds and the shakers' shaking speeds on the average amount of detached fruits does show some significant differences, at the level of significance 10 %. Clearly, the interaction effect between the beaters' shaking speed 40 in/sec and the forward speed of the harvester 1.20 mi/hr from one side, and interactions between the beaters' shaking speed 73 in/sec and machine

forward speed 0.90 mi/hr; beaters' shaking speed 56 in/sec and machine forward speed 1.20 mi/hr; and the beaters' shaking speed 56 in/sec and the forward speed 0.90 mi/hr, all on other side, recorded as having high significant differences on the average amount of detached grapefruits. Also, there were significant differences for the effect of the interaction between the harvester forward speed 1.20 mi/hr and the beaters' shaking speed 73 in/sec on one side, and both the interactions between the harvester beaters' shaking speed 56 in/sec and its forward speed 1.20 mi/hr; and the beaters' shaking speed 56 in/sec and the forward speed 0.90 mi/hr on the other side, on the average amount of detached grapefruits, at the 10 % level of significance. The interaction between the harvester forward speed 0.90 mi/hr with the beaters' shaking speed 40 in/sec, and the harvester beaters' shaking speed 56 in/sec with its forward speed 0.90 mi/hr, has a visible significant effect on the average amount of detached grapefruits. Besides that, there were no further significant differences between the effect of the other beaters shaking speeds and the harvester forward speeds interactions on each other regarding the average amount of detached fruits, at the level of significance 10 %.

On the other hand, for the remaining fruits on the tree canopies, the partial interaction effect between the harvester forward speeds and beaters shaking speeds on the attached fruits is shown in Table 4-17. The amount of this interaction ranged between a minimum 19 fruits/tree, which resulted from the interaction of the maximum forward speed 1.20 mi/hr and maximum beaters' shaking speed 73 in/sec, and the maximum of 97 fruits/tree, from the interaction between the highest machine forward speed 1.20 mi/hr and shaking speed 56 in/sec. It is clear that, the minimal amount of fruit remaining on the tree canopies resulted from the highest shaking speed 73 in/sec at both forward speeds 0.90 and 1.20 mi/hr. Also, by increasing the harvester forward speed from 0.90 mi/hr to 1.20 mi/hr, the amount of the fruit remaining on the

fruit trees is increased at the beaters' shaking speed 56 in/sec, while it is decreased at the shaking speed 73 in/sec from 24 fruits/tree to 19 fruits/tree, and decreased at the shaking speed 40 in/sec from 59 fruits/tree to 49 fruits/tree, by increasing the harvester forward speed. Meanwhile, at both machine forward speeds, the amount of fruit remaining on trees is increased by increasing the beaters shaking speed from 40 in/sec to 56 in/sec, while it is decreased at the highest shaking speed 73 in/sec. Statistically, at the 10 % level of significance, interactions between the harvester beaters shaking speeds and its forward speeds, did not make a significant differences on each other for the amounts of the grapefruits remaining on the tree canopies. But, there is an obvious significant effect for the interaction between the harvester forward speed 0.90 mi/hr with the highest beaters' shaking speed 73 in/sec, and the harvester beaters' shaking speed 56 in/sec with its forward speed 1.20 mi/hr, on the remaining fruits amount on the tree canopies, at a 0.90 confidence level.

In addition, from the amounts of detached fruit and the fruit remaining on the tree canopies, Table 4-18 shows the fundamental aspects of the interaction effect between the beaters shaking speed and the machine forward speed on the grapefruit detachment percentage. The average amount of fruit detachment percentage ranged between 7.11 %, due to the beaters' shaking speed 40 in/sec and forward speed 1.20 mi/hr interaction, and 41.58 % from the interaction of forward speed 0.90 mi/hr and shaking speed 73 in/sec. As observed from Table 4-18, at both harvester forward speeds, the fruit detachment percentage increased by increasing the beaters shaking speed from 40 in/sec to 73 in/sec, while the fruit detachment percentage is decreased at each beaters shaking speed by increasing the harvester forward speed from 0.90 mi/hr to 1.20 mi/hr. The highest fruit detachment percentage 41.58 % resulted from the interaction between the specific forward speed 0.90 mi/hr and shaking speed 73 in/sec. This

maximum percentage was obtained by operating the canopy shaker at the highest shaking speed with an enough period of time, which occurs for the lowest forward speed (0.90 mi/hr). The forward speed 0.90 mi/hr gave more time to the machine shakers to shake whole tree canopy. On the other hand, the minimum fruit detachment percentage 7.11 % occurred due to the interaction between the forward speed 1.20 mi/hr and the shaking speed 40 in/sec. This percentage was obtained because of the lowest shaking speed operation with the least amount of time, which occurred by the highest forward speed (1.20 mi/hr). The highest forward speed (1.20 mi/hr) may allow less time to shake the whole tree canopy. Statistical analysis showed that, the interaction effect of the harvester forward speeds and its beaters shaking speeds on the percentage of detachment fruit is considered as a high contributor at level of significance 10 %. Briefly, at 10 % level of significance, the interaction influence between the harvester beaters' shaking speed 40 in/sec with the harvester forward speed 1.20 mi/hr on one side, and all the other interactions between the harvester forward speeds and beaters shaking speeds on the other side, has meaningful influence on the fruit detachment percentage. In addition, influence of the interactions between the harvester beaters' shaking speed 73 in/sec with the harvester forward speed 0.90 mi/hr on one side, and the other interactions on other side, (machine forward speed 0.90 mi/hr with beaters' shaking speed 56 in/sec; machine forward speed 0.90 mi/hr with beaters' shaking speed 40 in/sec; machine forward speed 1.20 mi/hr with beaters' shaking speed 73 in/sec; and machine forward speed 1.20 mi/hr with the beaters' shaking speed 40 in/sec) have meaningful influence on the fruit detachment percentage at the 10 % level of significance. The statistical analysis demonstrated a non-significant difference between the interactions of some harvester forward speeds and its beaters shaking speeds on the fruit detachment percentage, when the level of significance is 10 %.

Table 4-16. The average of the detached fruit (fruits/tree).

Forward Speed (mi/hr)	Beaters Shaking Speed (in/sec)			Ave.
	40	56	73	
0.90	13^{bc}	31^{a}	17^{acd}	21
1.20	3^{b}	20^{ac}	8^{bd}	11
Ave.	10	28	12	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-17. The average of the adhered fruit on the trees (fruits/tree).

Forward Speed (mi/hr)	Beaters Shaking Speed (in/sec)			Ave.
	40	56	73	
0.90	59^{ac}	71^{ac}	24^{bc}	57
1.20	49^{ac}	97^{a}	19^{ac}	55
Ave.	55.56	79.67	21.50	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-18. The average of the grapefruit detachment percentage (%).

Forward Speed (mi/hr)	Beaters Shaking Speed (in/sec)			Ave.
	40	56	73	
0.90	23.30^{b}	29.76^{b}	41.58^{a}	29.54
1.20	7.11^{c}	19.07^{ab}	29.95^{b}	18.71
Ave.	17.90	26.20	35.77	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of the Interaction between the Machine Beaters' Shaking Speeds, Harvesting Tunnel Widths, and the Machine Forward Speeds on the Field Harvesting

The analysis that can lead to a satisfying decision about adjusting the harvesting machine's operational variables, which were chosen in this research study (harvester forward speed, beaters' shaking speed, and the harvesting tunnel width), is the interaction effect analysis, which was done using different operating variables. Table 4-19 shows the interaction effect between the three operating variables on the average amount of the detached grapefruits. It is observed that the detached fruit amount ranged between the lowest amount 3 fruits/tree that is due to the interaction between the initial beaters' shaking speed 40 in/sec, second machine forward speed 1.20 mi/hr, and the machine tunnel width 69 inches, while the highest detached fruit average amount equal to 47 fruits/tree, which is obtained because of the interaction between the initial forward speed 0.90 mi/hr, the shaking speed 56 in/sec, and internal harvesting width 69 inches. Also, as observed from the field data, the lowest amount is obtained with the highest forward speed (1.20 mi/hr) and the minimum shaking speed (40 in/sec), while the maximum amount of detached grapefruit is obtained by second beaters' shaking speed (56 in/sec) and first forward speed (0.90 mi/hr), which may mean that the shaking time that is obtained from the highest forward speed is less than the shaking time that is available by using the lowest machine forward speed. So, the minimum amount is obtained due to an inadequate shaking time and shaking speed, while the maximum detached grapefruit amount is obtained from a sufficient shaking time and shaking speed. The statistical analysis revealed that, the interaction effect between the beaters' shaking speed 56 in/sec, machine forward speed 0.90 mi/hr, and the default harvester's tunnel width 69 inches from one side, and all the other harvester operation variables from the other side, on the amount of detached fruits, shows a significant difference, at 10 % of the level of significance. Secondly, there is a significant effect as a result of interaction between

the beaters' shaking speed 40 in/sec, machine forward speed 1.20 mi/hr, and the default harvester's tunnel width 69 inches from one side, and the beaters' shaking speed 56 in/sec, machine forward speed 1.20 mi/hr, and the internal harvesting tunnel width 75 inches from the other side, on the amount of detached fruits, at a 0.90 confidence level. Thirdly, there is a significant difference between the interaction of the beaters' shaking speed 73 in/sec, machine forward speed 1.20 mi/hr, and the default internal tunnel width 69 inches from one side, and the beaters' shaking speed 56 in/sec, machine forward speed 0.90 mi/hr, and the internal harvesting tunnel width 75 inches from the other side, on the detached fruits amount at level of significance 10%. In contrast, there were no significant effects found due to interaction between other operating variables of the citrus harvester on the amount of detached grapefruits at the 10 % level of significance, as shown in Figure 4-1.

Data in Table 4-20 illustrates influence of the interaction between the machine internal tunnel widths, beaters shaking speeds, and the machine forward speeds on the average amount of the fruits remaining on the tree canopies. As observed from the obtained data, the lowest amount of remained fruit is 19 fruits/tree, due to the interaction between the machine forward speed 1.20 mi/hr, the beaters' shaking speed 73 in/sec, and the internal tunnel width 69 inches, while the highest amount of remained fruit 97 fruits/tree, was a result of the interaction between the machine forward speed 1.20 mi/hr, beaters' shaking speed 56 in/sec, and the internal tunnel width 75 inches. The reason for such huge amounts of fruits remaining on the grapefruit canopies is the second harvesting tunnel width (75 inches), which resulted in lesser beaters' penetration into the tree canopies than that acquired by the harvesting width 69 inches. This constituted lower penetration than required between the shaking beaters of the harvesting machine and the grapefruit tree canopies.

Furthermore, the statistical analysis proved that, there are significant differences from the effect of interactions between the forward speed 1.20 mi/hr, beaters' shaking speed 73 in/sec, and tunnel width 69 inches from one side, and interactions between the forward speed 0.90 mi/hr, beaters' shaking speed 40 in/sec, and tunnel width 75 inches; and the forward speed 1.20 mi/hr, beaters' shaking speed 56 in/sec, and tunnel width 75 inches from the other side, on the amount of fruit remaining on the tree canopies, at the 10 % level of significance. Also, there is a significant difference by the effect of the interactions between the forward speed 0.90 mi/hr, shaking speed 73 in/sec, and the tunnel width 75 inches; and also the forward speed 1.20 mi/hr, beaters' shaking speed 56 in/sec, and the harvesting tunnel width 75 inches on the amount of remaining fruit on the tree canopies at level of significance 10 %. Also, at the same level of significance, there is a significant difference from the interactions between the forward speed 0.90 mi/hr, beaters' shaking speed 40 in/sec, and the default harvesting tunnel width 69 inches on one side, and the first forward speed 0.90 mi/hr, beaters' shaking speed 40 in/sec, and the harvester's tunnel width 75 inches at other side, on the amount of fruit remaining on the tree canopies. There were no significant effects found by the other operating variable interactions on the amount of remaining fruit on the tree canopies at the 10 % level of significance, as shown in Figure 4-2.

Additionally, the critical scientific decision about the appropriateness of the selected operating variables (two machine forward speeds, three beaters' shaking speeds, and two harvesting tunnel widths) of the new prototype of the fruit harvesting machine may precisely be taken from the calculation results of the percentage of the detached fruit. Table 4-21 shows the effect of interaction between the three operating variables (machine forward speed, beaters' shaking speed, and the harvester' tunnel width) on the average amount of fruit detachment

percentage. The result of that interaction reveals that the highest percentage of detached fruit is 41.58 % as a result of interaction between the third beaters' shaking speed 73 in/sec, first machine forward speed 0.90 mi/hr, and the harvesting tunnel width 75 inches. This high percentage of detached fruit may have resulted from a combination of the lowest forward speed, which provided enough shaking time to shake the whole tree canopy synchronously with an adequate shaking speed 73 in/sec. Furthermore, obtained data shows that the lowest percentage of detached grapefruit is 7.11 % as a result of interaction between the first shaking speed 40 in/sec, second machine forward speed 1.20 mi/hr, and the harvesting tunnel width 69 inches. This lowest percentage of detached fruits resulted from the maximum forward speed, which does not provide enough shaking time to shake the whole tree canopy synchronously with the lowest shaking speed (40 in/sec). As observed from the data obtained with the harvesting tunnel width 75 inches, and the forward speed of 0.90 mi/hr, by increasing the beaters' shaking speed from 40 in/sec to 73 in/sec, the proportion of detached fruits is increased from 12.45 % to 41.58 %. Also, even with the tunnel width of 69 inches, the detachment percentage of the grapefruit is increased from 34.14 % to 38.05 % by increasing the shaking speed from 40 in/sec to 56 in/sec, respectively. Also, overall higher percentages of detached fruits are obtained with the first machine forward speed (0.90 mi/hr) compared to the second speed (1.20 mi/hr).

Statistically, there are significant differences for the interaction effects between the forward speed 0.90 mi/hr, beaters' shaking speed 40 in/sec, and tunnel width 75 inches from one side, and the interactions between the forward speed 0.90 mi/hr, beaters' shaking speed 56 in/sec, and tunnel width 69 inches; and also the forward speed 0.90 mi/hr, beaters' shaking speed 73 in/sec, and tunnel width 75 inches from the other side, on the percentage of the detached grapefruits when the level of significance is 10 %. Also, there are noticeable differences for

effect of the interaction between the forward speed 1.20 mi/hr, beaters' shaking speed 40 in/sec, and tunnel width 69 inches on one side, and the forward speed 0.90 mi/hr, beaters' shaking speed 40 in/sec, and tunnel width 69 inches; the forward speed 0.90 mi/hr, shaking speed 56 in/sec, and tunnel width 69 inches; and also the forward speed 0.90 mi/hr, shaking speed 73 in/sec, and the tunnel width 75 inches, all from the other side, on the fruit detachment percentage at the 10 % level of significance. As well as, there is a significant difference by effect of the interaction between the forward speed 1.20 mi/hr, beaters' shaking speed 56 in/sec, and the tunnel width 75 inches on one side, and the interaction between the forward speed 1.20 mi/hr, beaters' shaking speed 73 in/sec, and tunnel width 69 inches on the other side, at the 10 % level of significance. There were no significant effects found by the other operating variable interactions on the fruit detachment percentage, as shown in Figure 4-3 below.

In conclusion, it should be noted that for both tunnel widths 75 and 69 inches, increasing the shaking speed from 40 in/sec to 73 in/sec at harvester forward speed 0.90 mi/hr has a favorable interaction on the grapefruit detachment percentage. So, the best decision from the pre-test results as shown in Table 4-21, is operating the new prototype of a self-propelled over the top citrus harvesting machine using canopy shaker at the harvester forward speed 0.90 mi/hr, tunnel width 75 inches, and shaker shaking speed 73 in/sec, where the maximum grapefruit detachment percentage, 41.58 % was obtained.

Table 4-19. The average of the detached fruit (fruits/tree).

Tunnel Width (in)	Harvester Forward Speed (mi/hr)						
	0.90 (Mfd1)			1.20 (Mfd2)			
	Canopy Shakers Speed (in/sec)			Canopy Shakers Speed (in/sec)			
	40 (Shs1)	56 (Shs2)	73 (Shs3)	40 (Shs1)	56 (Shs2)	73 (Shs3)	Ave.
75 (Tw2)	12^{bc}	16^{be}	17^{bc}	---	20^{bd}	---	16
69 (Tw1)	14^{bc}	47^{a}	---	3^{ce}	---	8^{cd}	18
Ave.	13	31	17	3	20	8	
Shakers speed	10		28		12		
Harvester speed	21			11			

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

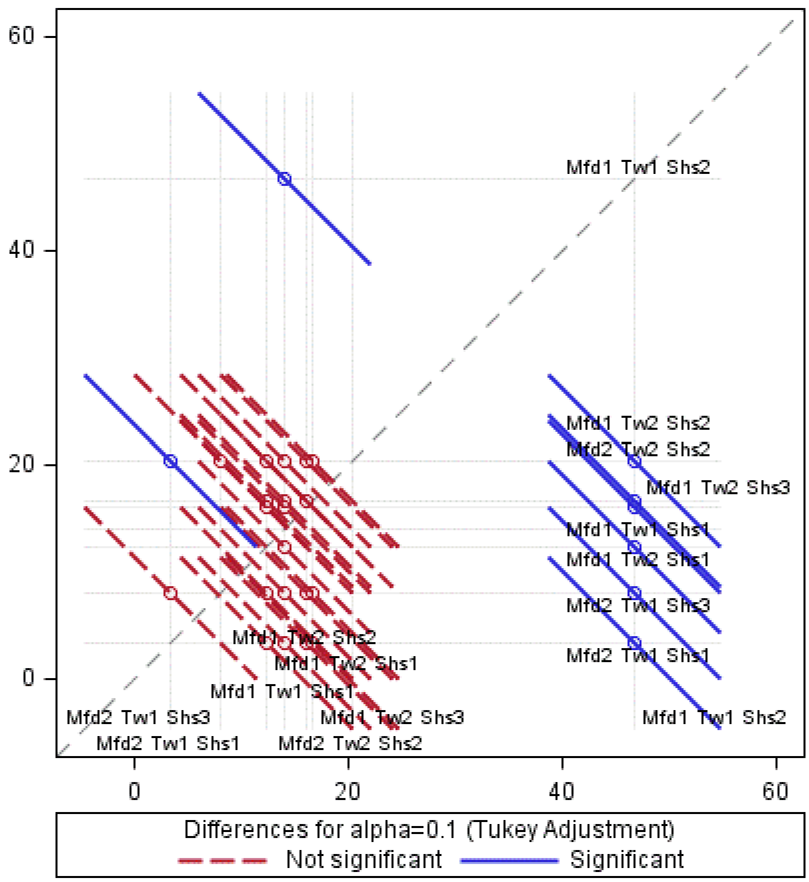

Figure 4-1. Comparison results for the effect of the interaction between the three operating variables on the amount of the detached grapefruit (fruits/tree).

Table 4-20. The average of the adhered fruit on the trees (fruits/tree).

Tunnel Width (in)	Harvester Forward Speed (mi/hr)						
	0.90 (Mfd1)			1.20 (Mfd2)			
	Canopy Shakers Speed (in/sec)			Canopy Shakers Speed (in/sec)			
	40 (Shs1)	56 (Shs2)	73 (Shs3)	40 (Shs1)	56 (Shs2)	73 (Shs3)	Ave.
75 (Tw2)	85^{ad}	64^{ab}	24^{bd}	---	97^{ac}	---	67
69 (Tw1)	32^{bc}	78^{ab}	---	49^{ab}	---	19^{b}	45
Ave.	59	71	24	49	97	19	
Shakers speed	56		80		22		
Harvester speed	57			55			

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

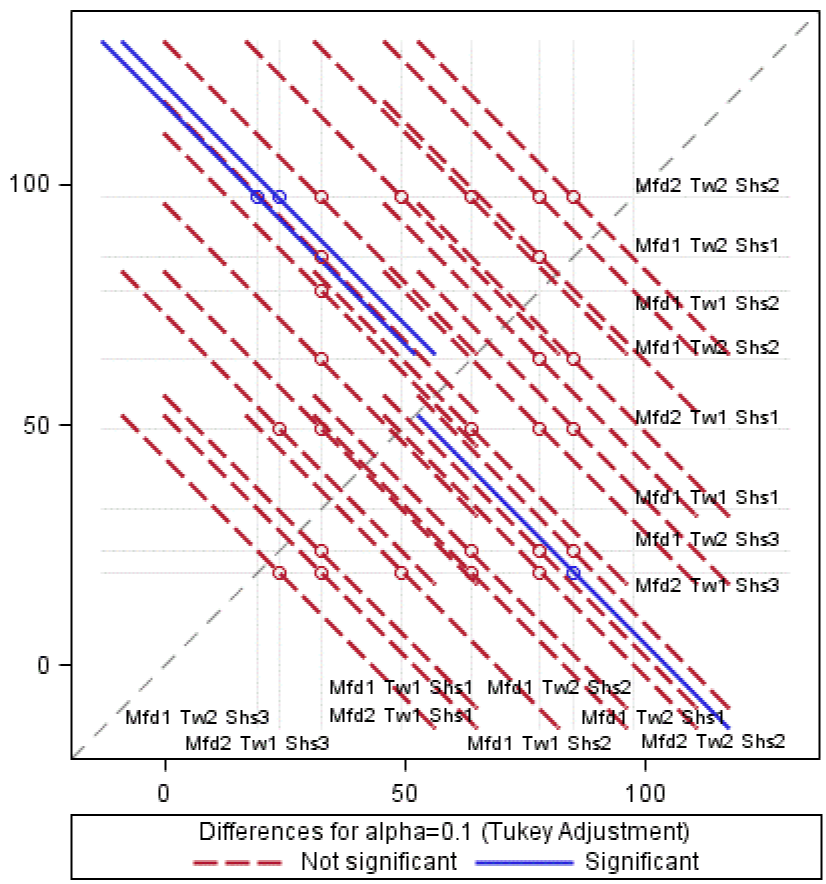

Figure 4-2. Comparison results for the effect of the interaction between the three operating variables on the amount of remaining grapefruit on the trees (fruits/tree).

Table 4-21. The average of the fruit beads detachment percentage (%).

Tunnel Width (in)	Harvester Forward Speed (mi/hr)						
	0.90 (Mfd1)			1.20 (Mfd2)			
	Canopy Shakers Speed (in/sec)			Canopy Shakers Speed (in/sec)			
	40 (Shs1)	56 (Shs2)	73 (Shs3)	40 (Shs1)	56 (Shs2)	73 (Shs3)	Ave.
75 (Tw2)	12.45^{bc}	21.47^{ab}	41.58^{ad}	---	19.07^{bd}	---	23.64
69 (Tw1)	34.14^{acd}	38.05^{ad}	---	7.11^{be}	---	29.95^{ace}	27.31
Ave.	23.30	29.76	41.58	7.11	19.07	29,95	
	17.90		26.20		35.77		
	29.54			18.71			

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

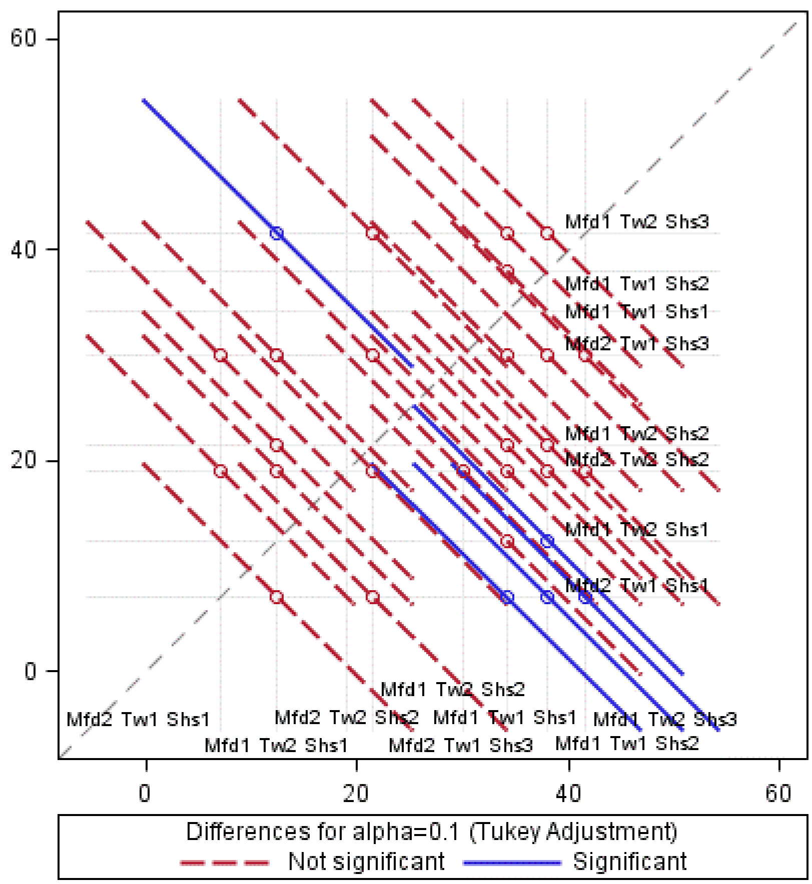

Figure 4-3. Comparison results for the effect of the interaction between the three operating variables on the grapefruit detachment percentage (%).

Distribution of Acceleration Magnitude in the Grapefruit Tree Canopy

Physically, fruits are harvested when the tensile force between the fruit calyx and the peduncle (stem) exceed the fruits adhesion force, and thus severs the adhesion layer. The adhesion force is variable according to fruit maturity. Several experiments of canopy shaking were done on grapefruit trees, to study the branch's dynamic behavior (acceleration upon shaking) during beaters operation with the preliminary prototype citrus harvesting machine (7 beaters per shaking unit). Numerous small acceleration devices (15 USB accelerometer sensors model X16-1C) were placed on various branches, at randomly selected locations in the canopy of a fruit tree (Ray Ruby grapefruit), using plastic adhesive tape, as shown in Figure 3-39. The resulting distribution of canopy accelerations were obtained under various operating conditions mentioned in this research study (two beaters' shaking speeds and three beaters' penetrations into the canopy), where the harvester's tunnel width was kept constant at 69 inches. Data configuration is displayed using the Java XLR8R program that is furnished with each X16-1C sensor, where the magnitude of the acceleration is calculated and stored internally in the X16-1C (i.e., internal calculation). Also, the results of the tree branches' oscillation during shaking were recorded with the global clock, for a precise time (msec), and cluster of three coordinate accelerations (x, y, and z). Subsequently, the acceleration data were found by using the time domain diagram (at x-axis, msec) on x, y, and z axes, which were initially recorded at sample rate of 50 Hz and sample size 30,000 (counts), versus time domain magnitude of the converted data (at the y-axis, gravitational acceleration, g). Then, the resultants of the three coordinate axes are calculated and displayed, and figures generated using the MATLAB® program.

Shaking Acceleration Distribution by Diverse Beaters Penetrations into the Harvested Grapefruit Canopies

The results of Table C-1, present the time domain magnitudes and averages of the acceleration that were achieved by operating the harvester's beaters at three different tree canopy penetrations (default position 10, 11, and 12 inches turn buckle length), with a constant beaters shaking speed of 45.30 in/sec and approximately 0.80 mi/hr of the machine forward speed, where 15 sensors were deployed into one grapefruit tree canopy. The distribution of the acceleration resulting from shaking the tree canopy was uneven, with diversity in the magnitudes of acceleration, as shown in the following Figures 4-4, 4-5, and 4-6. The branches' behavior changed along the tree canopy cross-section (laterally and vertically). The maximum average magnitude was equal to 7.804 g, which was achieved by extending the beaters deeper into the tree canopy, which was accomplished by increasing the length of the turn buckles between the crank-shaft and the beaters to 12 inches. The maximum magnitude, recorded at the left side of the tree, was achieved by setting the left beaters squad on maximum turn buckle length (12 inches), while the minimum average magnitude of 1.691 g was recorded at the top central band of the tree perimeter using 11 inches of turn buckle length. Furthermore, as a result of moving the beaters out to the canopy perimeter edge, by decreasing the length of each turn buckle to 10 inches, and running the right beaters squad, the maximum magnitude equal to 6.074 g was recorded at the lower front edge of the tree perimeter. The maximum magnitude gained by increasing the beaters' penetration to 11 inches, again using the right beaters squad, was 7.255 g, also recorded at the lower front edge of the tree perimeter. The maximum magnitude (7.255 g) also resulted at the lower right side of the tree perimeter from operating the right beaters squad, while the minimum magnitude value was 1.691 g, recorded at the top central edge of the tree perimeter.

At the top of the tree canopy (sensors 2, 8, and 9), the magnitude increased from 2.740 g to 4.319 g by increasing the beaters penetration (increasing the connecting turn buckle length from 10 to 11 inches), but decreased to 1.988 g, which recorded by sensor number 2 under the right beaters' influence, with the turn buckle length increased to 12 inches. With the left beaters operation, the magnitude increased from 1.910 g to 3.450 g, as recorded by sensors 8 and 9, by increasing the harvester's penetration (increasing length of the connecting rod from 10 to 12 inches). Also, the acceleration magnitude value at the central edge of the tree perimeter and parallel to the forward machine speed track, as recorded by sensor number 15 (underneath of the canopy and 20 inches rear of the main trunk), increased from 1.971 g to 2.207 g by increasing both beaters' squads (left and right unit) penetration from 10 to 11 inches, and again, the magnitude decreased by using a turn buckle length of 12 inches. In the lower part of the tree canopy where sensors 3, 10, 12, and 14 were located on left and right sides of the grapefruit tree, the maximum acceleration magnitude was 6.207 g, using the 12 inches turn buckle connection for left the side, and 7.255 g using 11 inches turn buckle connection for the right side. Generally, depending on the sensors location, the acceleration magnitude imparted by the beaters, at all beaters' penetration settings, was substantially higher on the lower branches than on the branches on the central top of the tree canopy, or the limbs along the central band of the tree canopy (sensor number 15). Also, on the lateral branches above 40 inches from the ground, the right side of the tree canopy had a slightly higher acceleration magnitude (Ave. 3.93 g) than the left side (Ave. 3.52 g) of the tree canopy, while the branches in the center of the tree canopy had a lower acceleration magnitude average for all beaters' penetration settings. So, in summary, the tree canopy was receiving different shaking magnitudes from the two beaters' squads (left and right harvester units), when the two crank-shaft motors operated.

In general, the average magnitude of the gravitational acceleration (g) ranged between 3.403 g obtained by operating the two shaking beaters units on 10 inches turn buckle setting, and 3.848 g obtained by operating the shaking beaters on 12 inches turn buckle setting. As observed, by increasing the shaking beaters penetration into the tree canopy, the average magnitude of acceleration (g) on the trees' branches increased. So, the overall influence of beaters vibration on tree branches was increased with an increase in the shaking beaters penetration displacement. Statistically, Table C-1 shows that there is an observable significant difference at the 10 % level of significance, for the influence of the penetration of harvesting machine beaters on the amount of the acceleration magnitude of the tree branches, between the turn buckle length of 10 inches, and the turn buckle length of 12 inches. Otherwise, there are no significant differences, at the 10 % level of significance, between the turn buckle length of 10 inches, and the turn buckle length of 11 inches, or between the turn buckle length of 11 inches and the turn buckle length of 12 inches, on the acceleration magnitude of the grapefruit tree branches. Also there is no further significant difference for the effect of both the tree canopy sides (3.52 g at left and 3.93 g at right) on the acceleration magnitude, at the level of significance 10 %.

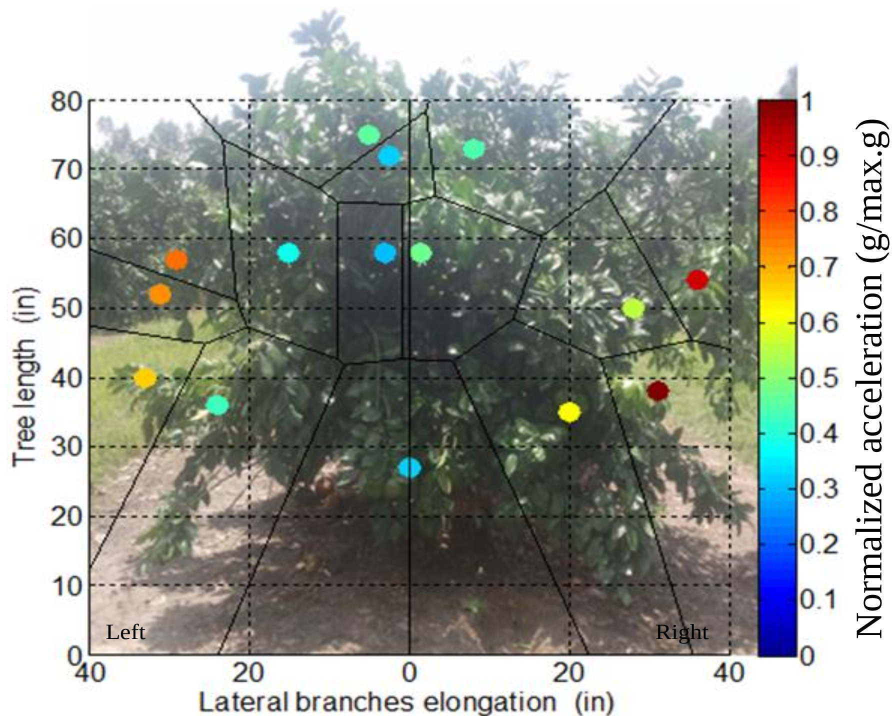

Figure 4-4. Acceleration magnitude distributions into the grapefruit tree canopy by 10 inches of turn buckle length (front view). [Photo courtesy of Naji Al-Dosary]

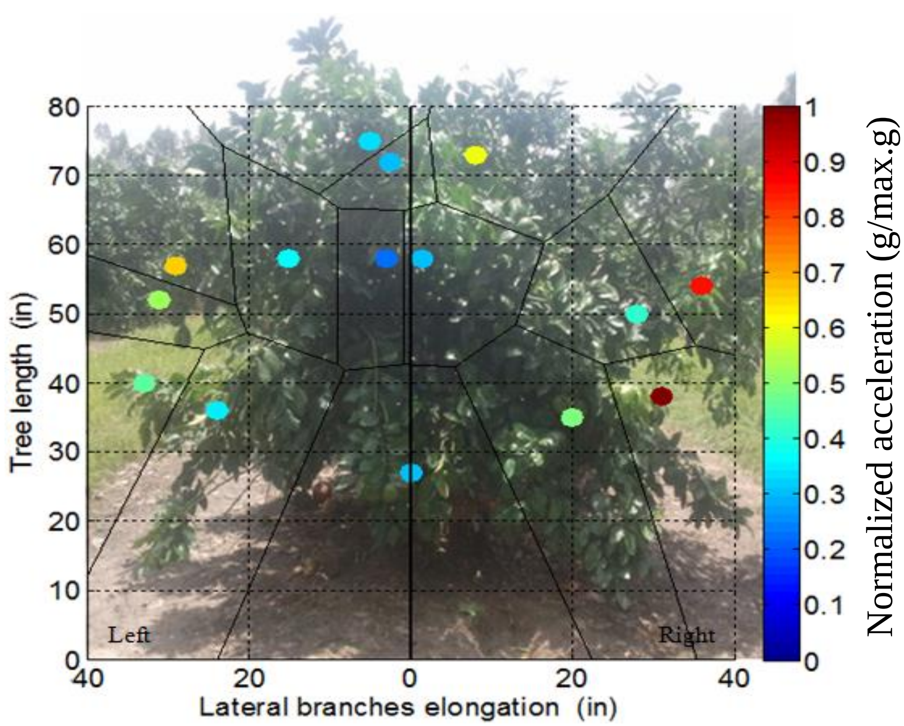

Figure 4-5. Acceleration magnitude distributions into the grapefruit tree canopy by 11 inches of turn buckle length (front view). [Photo courtesy of Naji Al-Dosary]

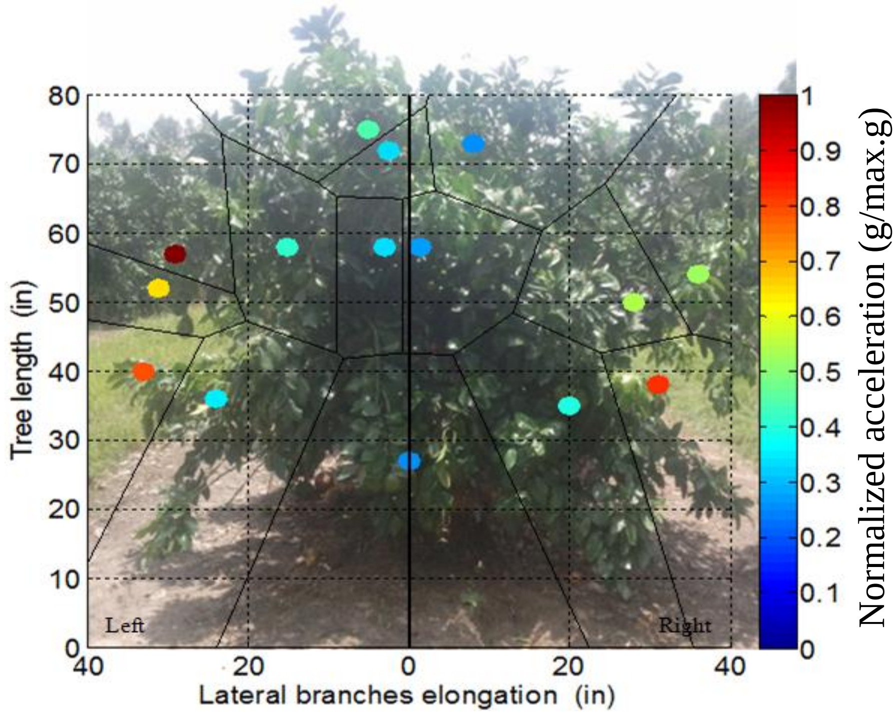

Figure 4-6. Acceleration magnitude distributions into the grapefruit tree canopy by 12 inches of turn buckle length (front view). [Photo courtesy of Naji Al-Dosary]

Shaking Acceleration Distribution Effect by Various Beaters' Shaking Speeds

For this experiment, 15 USB accelerometer sensors (model X16-1C) were placed on various branches at different locations, on three random tree canopies of grapefruit (Ray Ruby grapefruit), with 5 sensors placed into each individual grapefruit tree canopy. The results of the acceleration magnitude distribution on the shaking tree canopies were obtained by using various shaking speeds of the harvester's beaters as referenced in Table C-2.

The results of Table C-2 show the time domain magnitudes and averages of the acceleration that were achieved by operating the shaking beaters at two different shaking speeds (45.30 and 65.90 in/sec), by setting the knobs of both left and right flow control valves at similar turns (2.50 and 3.0 turns), while keeping the shaking beaters' penetration into the grapefruit canopy constant at 12 inches turn buckle length and approximately 0.80 mi/hr of the machine

forward speed. The distribution of the acceleration from the shaking beaters operations on the tree canopy was non-uniform with diversity in the magnitudes of the acceleration (g) as represented in Figures 4-7 and 4-8. As previously noted, the tree branch behaviors changed along the tree canopy perimeter (laterally and vertically). The maximum average of the acceleration magnitude was 8.00 g, obtained at the right side of the tree perimeter (sensor number 14) for beaters squads' angular velocity of 65.90 in/sec, while the minimum average magnitude was 2.286 g resulting from the 45.30 in/sec beaters' speed. The maximum magnitude was obtained at the left side of the tree perimeter by running the beaters' squad on the second speed (65.90 in/sec) achieving 5.907 g, while the lowest beaters' speed (45.30 in/sec) yielded the minimum magnitude of 2.409 g at sensor number 13. At the top of the tree canopy (more than 52 inches from the ground), the magnitude increased from 2.286 g to 6.947 g, by increasing the harvester beaters' speed from 45.30 in/sec to 65.90 in/sec, which resulted from the right beaters influence. However, the left beaters' operation, as recorded by sensors 2 and 7, saw an acceleration magnitude increase from 3.01 g to 5.907 g, by increasing the harvester beaters' speed to 65.90 in/sec. At the top central edge of the tree perimeter, the acceleration magnitude increased from 2.286 g to 3.425 g by increasing both beaters squads' speed. The magnitude at the central edge of the tree perimeter, and parallel to the machine path, recorded at sensor number 3 (underneath of the tree canopy and 21 inches behind the main trunk), decreased from 2.088 g to 1.933 g, by increasing the beaters' speed from 45.30 in/sec to 65.90 in/sec. Measurements were also taken at both left and right sides of the lower canopy perimeter at heights of 45 inches from the ground and less. The maximum right side acceleration magnitude average was 8.00 g at beaters speed of 65.90 in/sec and 7.387 g at beaters speed of 45.30 in/sec. In addition, the maximum left side acceleration magnitude was 4.884 g at a beaters speed of 65.90 in/sec, and 3.756 g at a beaters

speed of 45.30 in/sec. Accordingly, as shown in Figures 4-7 and 4-8, the comparison of results from different sensors locations showed that the shaking beaters acceleration magnitude, at all beaters' shaking settings, was substantially higher at lower branches in the tree canopy (45 inches from the ground and less), than the acceleration magnitude of branches on the top central of the tree canopy, and along the central band of the tree canopy (sensor number 3). It appeared that the lateral branches, which are 45 inches and more from the ground on the left side of the tree canopy, received more acceleration magnitude (4.113 g) than the right side (4.109 g) of the tree canopy. Finally, the branches in the central band of the tree canopy have a low acceleration magnitude average at all beaters' shaking settings.

In general, the average magnitude of the gravitational acceleration (g) ranged between 3.65 g and 5.055 g, when both shaking beaters units (right and left) where operated at 45.30 in/sec, and 65.90 in/sec, respectively. As observed, by increasing the shaking beaters' speed from 45.30 in/sec to 65.90 in/sec, the average magnitude of the acceleration (g) on the trees branches will be increased, so the influence of the beaters shaking speed on tree branches is to increase acceleration. Statistically, the small letters in Table C-2 shows that there is no significant difference, at the level of significance 10 %, for the influence of the shaking speed of the machine beaters on the amount of the acceleration magnitude of the tree branches, between the lowest shaking speed (45.30 in/sec) and the highest shaking speed (65.90 in/sec). Likewise, there is no further significant difference between the effects of the two different beaters shaking speeds for both tree canopy sides (4.113 g left & 4.109 g right side) on the average amount of the acceleration magnitude, at the level of significance 10 %.

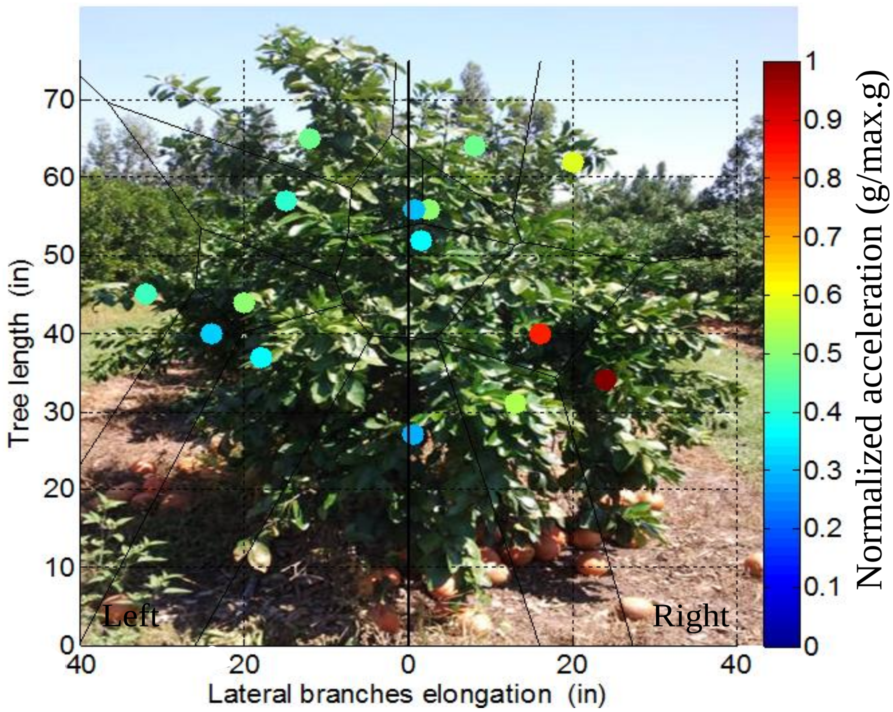

Figure 4-7. Acceleration magnitude distribution into the grapefruit tree canopy by the first beaters shaking speed (front view). [Photo courtesy of Naji Al-Dosary]

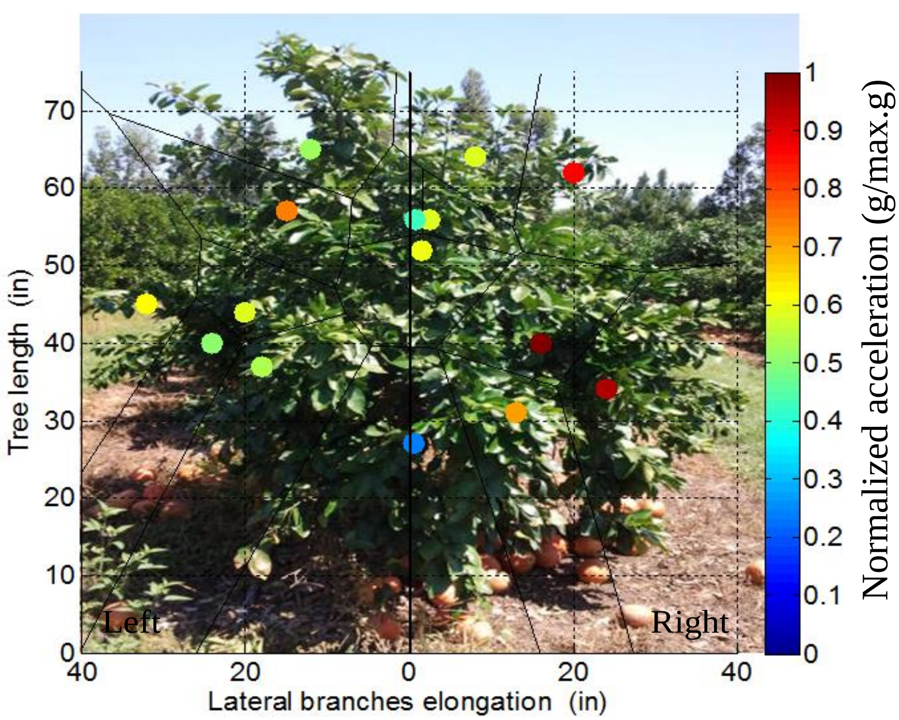

Figure 4-8. Acceleration magnitude distribution into the grapefruit tree canopy by the second beaters shaking speed (front view). [Photo courtesy of Naji Al-Dosary]

Distribution of Acceleration Magnitude on the Harvester's Shakers

For the acceleration measurement trials of the harvester's beaters, without resistance loads from the grapefruit trees canopies, 6 USB accelerometer sensors model X16-1C were placed on various harvester's beaters at different locations, and attached using plastic adhesive tape. There were 3 sensors stuck on 3 different beaters of each shaker unit (3 sensors on right and 3 on left), as shown in Figure 4-9. For these trials, the 1/2" (OD) hollow PVC pipes were replaced with 32 inches long flexible 1" (OD) round grey PVC rods. The total length of each single beater is 60 inches, connected to 11.50 inches turn buckle length. The first test of these PVC rods revealed that a quick fatigue can occur next to the joining metal sleeve for joining a steel pipe with a PVC rod, when using a high shaking speed of more than 101.50 in/sec. So, the higher shaking speed, beyond 101.50 in/sec, was excluded from the testing. The result of the acceleration magnitude distribution on the shaking beaters was obtained by operating the beaters at two different shaking speeds (69.32 and 101.50 in/sec) established by setting the two knobs of the flow control valves at 2.0 and 2.5 respectively, as shown in Tables 4-22 and 4-23.

When the individual shakers were operated at speed of 69.32 in/sec, the average magnitude of the acceleration ranged between 5.43 g and 6.65 g, and when operating the individual shakers at shaking speed 101.50 in/sec, the lowest magnitude was 9.18 g and the highest magnitude was 10.39 g. In general, by increasing the shaking beaters' speed from 69.32 in/sec to 101.50 in/sec, the average magnitude amounts of the acceleration (g) on the harvester beaters will be increased. However, at the first speed 69.32 in/sec, the right shaker unit gives a higher acceleration magnitude than the left shaker unit. In contrast, at the second speed 101.50 in/sec, the right shaker unit gave an acceleration magnitude less than the left shaker unit, as illustrated in Tables 4-22. Furthermore, from the statistical analysis as shown by small letters at each row in Table 4-22, it was found that there is a significant difference between the two shaker

units locations (right or left shakers) on the amount of the acceleration magnitude, which was obtained from sensors on the shaking beaters operated at both shaking speeds (69.32 and 101.50 in/sec), at the level of significance 10 % when the two shaker units were operated separately.

In terms of shaking the two machine's beaters units together at the same time, the average acceleration magnitude ranged between 5.04 g by the right unit and 5.38 g by the left shaker unit at shaking speed 69.32 in/sec, while there was no difference between the right and left shakers magnitude (10 g) at the shaking speed 101.50 in/sec. But in general, by increasing the shaking beaters' speed from 69.32 in/sec to 101.50 in/sec, the average acceleration magnitude of the two shaker units will increase when operating the two shaking beaters units simultaneously, as calculated in Tables 4-23. Statistically, the small letters in Table 4-23 show that there are no significant differences at the 10 % level of significance for influence of the shakers' location (right or left shakers) on the amount of the acceleration magnitude of the shaking beaters when the two shaker units operated simultaneously at different shaking speeds (69.32 and 101.50 in/sec).

That diversity of the shaking distribution of the harvester's beaters may have been caused by the fact that either the two flow control valves of the John Deere relief valves were not adjusted accurately for both harvester units (two crank-shafts) to be precisely the same rotational speed, or because of the hydraulic circuit that is connected to the right relief valve is longer than the circuit to the left relief valve.

Meanwhile, if the two shakers' motors performance is taken as a comparison of the two shaker units' acceleration magnitudes, the results show that by operating the two shakers' motors separately, the two shakers' motors (right and left) have no significant differences at the level of significant 10 % on the acceleration magnitude where their magnitudes are equal 7.91 g. On the

other hand, when the two shakers' motors were operated simultaneously, the acceleration magnitude of the right shakers' motor is 7.57 g, and the left shakers' motor offered more acceleration magnitude equal to 7.69 g, but without significant differences at 10 % level of significance. In general, there is no significant difference between testing the two shakers' motors individually, or together, on the acceleration magnitude results. The average magnitude that was recorded by running the two shakers' motors independently was 7.91 g and synchronized operation was 7.63 g. Consequently, from the shakers experiment results, there were no considerable differences between the obtained acceleration magnitudes that resulted by operating the two shakers units either independently or together, which means the two shaker units were functioning adequately as required by the canopy shaker field trials.

Figure 4-9. Acceleration sensors posted on some harvester’s beaters kind of PVC rods. [Photo courtesy of Naji Al-Dosary]

Table 4-22. The average magnitude of the acceleration (g) among the harvester's beaters depending on operating the two beater units independently at two shaking speeds.

No. of Sensor	Beaters Speed at Sensors Spot (inch/sec)	Acceleration Magnitude of the Left Shakers Unit (g)		Acceleration Magnitude of the Right Shakers Unit (g)		No. of Sensor
		Ave. of the Max. Accel. Mag. (g)	Ave. Accel. at each Shaking Period (g)	Ave. of the Max. Accel. Mag. (g)	Ave. Accel. at each Shaking Period (g)	
4	69.32	4.92	1.84	6.73	2.24	1
	101.5	9.64	4.11	9.1	4.03	
5	69.32	5.28	1.84	6.82	2.29	2
	101.5	10.65	4.26	9.3	3.99	
6	69.32	6.09	2.2	6.39	2.06	3
	101.5	10.88	4.2	9.13	3.94	
Average of Low Shaking Speed		5.43[b]	1.96	6.65[a]	2.20	
Average of High Shaking Speed		10.39[a]	4.19	9.18[b]	3.99	
Total Averages		7.91[a]		7.91[a]		

Each row averages, which have been followed by different letter, have significant differences among them statistically at a 0.90 confidence level.

Table 4-23. The average magnitude of the acceleration (g) among the harvester's beaters depending on operating the two beater units simultaneously at two shaking speeds.

No. of Sensor on Left	Beaters Speed at Sensors Spot (inch/sec)	Acceleration Magnitude of the Left Shakers Unit (g)		Acceleration Magnitude of the Right Shakers Unit (g)		No. of Sensor on Right
		Ave. of the Max. Accel. Mag. (g)	Ave. Accel. at each Shaking Period (g)	Ave. of the Max. Accel. Mag. (g)	Ave. Accel. at each Shaking Period (g)	
4	69.32	4.8	1.8	4.86	2.09	1
	101.5	9.01	3.96	10	4.2	
5	69.32	5.36	1.84	4.94	2.26	2
	101.5	10.64	4.19	10.29	3.81	
6	69.32	5.98	2.24	5.32	2.18	3
	101.5	10.35	4.23	9.99	3.81	
Average of Low Shaking Speed		5.38[a]	1.96	5.04[a]	2.18	
Average of High Shaking Speed		10.0[a]	4.13	10.09[a]	3.94	
Total Averages		7.69[a]		7.57[a]		

Averages, which have been followed by the same letter in each row, do not have significant differences among them statistically at a 0.90 confidence level.

Final Results of the Final Citrus Harvesting Machine Design

Effect of the Harvesting Machine Forward Speeds on the Field Harvesting

The follow discussion pertains to harvesting results for the final machine modifications and field trials conducted in January 2014, at the Plant Science Research and Education Center in Citra (PSREC), FL.

Table 4-24 shows effects of the forward speeds of the final harvesting machine design on the amount of grapefruits harvested from the tree canopies. In general, machine forward speed correlates with the required time for shaking tree canopies, where increasing the harvester forward speed, the resulting total canopies shaking time will be decreased, and shaking time was increased with lower forward speeds. From the field operations, it was found that the shaking time resulting from an average harvester's forward speed of 1.42 mi/hr was almost 3.88 sec/tree, while the shaking time resulting from the average harvester's lowest forward speed of 0.62 mi/hr was almost 8.75 sec/tree. It was found that the average amount of harvested grapefruit decreased at the higher forward speed 1.42 mi/hr achieving the lowest average detached fruit of 79 fruits/tree. The average amount of grapefruits ranged between 79 fruits/tree for the higher forward speed 1.42 mi/hr and 94 fruits/tree for the lower forward speed (0.62 mi/hr). Thus, by applying the statistical analysis to the field data, it was found that, with 10 % level of significance, there is an obvious significant difference between the influence of the low and high speed on the amount of detached grapefruits. Meanwhile, the influence of the harvester forward speeds on the fruit dislodgement percentage is shown in Table 4-25. The table shows that by increasing the harvester's forward speed from 0.62 mi/hr to 1.42 mi/hr, the average percentage of the detached grapefruits will be decreased from 80.03 % to 72.98 %, respectively. From the results analysis, it was found that, statistically, there is a clear significant difference at the 10 %

level of significance of the influence of the harvesting machine forward speeds on the percentage of the detached grapefruits.

Table 4-24. The average of the detached fruit (fruits/tree).

	Forward Speed of the Harvester (mi/hr)	
	0.62	1.42
Symbol	Mfd1	Mfd2
Ave. *	94[a]	79[b]
S.D.	39.40	31.45

* Averages, which have been followed by the same letter in the row, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-25. The average of the fruits detachment percentage (%).

	Forward Speed of the Harvester (mi/hr)	
	0.62	1.42
Symbol	Mfd1	Mfd2
Ave. *	80.03[a]	72.98[b]
S.D.	13.97	16.13

* Averages, which have been followed by the same letter in the row, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of Beaters Positions of the Harvesting Machine on the Field Harvesting

The results of the harvester's beaters positions (i.e., turn buckles lengths) influence on the amount of the detached fruit are shown in Table 4-26. Numerically, the position of the beaters default setting (component of different lengths of the harvester's turn buckles, 12, 14, and 15 inches) reveals a high amount of dislodged fruits (115 fruits/tree), while the short 12 inches turn buckles setting gave lower detached numbers of 59 fruits/tree. The reason for the decreased numbers may be that the machine's beaters are covering and shaking the lateral width of the tree canopy without penetrating the tree canopy sufficiently to dislodge inner fruits. Statistically, there were significant differences at the level of 10 % significance of the effect of the beaters positions on the average of the dislodgement quantity of grapefruits. In addition, data in Table 4-

27 illustrates the influence of the beaters penetrations into the tree canopy on the average of the fruits dislodgement percentage. As shown in Table 4-27, the fruit dislodgement percentage is increased by increasing the beaters penetration into the grapefruit canopy. In other words, increasing the turn buckle length from 12 to 16 inches, leads to increase in the percentage of grapefruit dislodgement from 62.32 % to 87.97 %. According to statistical analysis, at the 10 % level of significance, it was found that, there were visible significant differences between the effectiveness of the three beaters positions on the fruits dislodgement percentage (%).

Table 4-26. The average of the detached fruit (fruits/tree).

	Beaters Position (in), (turn buckle length)		
	12	Default Setting	16
Symbol	Bp1	Bp2	Bp3
Ave. *	59[c]	115[a]	86[b]
S.D.	19.89	38.38	22.28

* Averages, which have been followed by the same letter in the row, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-27. The average of the fruits detachment percentage (%).

	Beaters Position (in), (turn buckle length)		
	12	Default Setting	16
Symbol	Bp1	Bp2	Bp3
Ave. *	62.32[c]	79.25[b]	87.97[a]
S.D.	13.91	10.66	8.31

* Averages, which have been followed by the same letter in the row, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of Shaking Speeds of the Harvester's Beaters on the Field Harvesting

In terms of the machine beaters frequency, Table 4-28 shows the influence of the machine beater's speeds on the average amount of detached grapefruit (fruits/tree). When the beaters' shaking speed is increased from 56.50 in/sec to 73 in/sec, the average amount of fruit detached increased from 78 fruits/tree to 95 fruits/tree. From the statistical analysis at the 10 % level of significance, it was found that, there is a significant difference between the influences of the beater's speeds 56.50 in/sec and 73 in/sec, on the average amount of the detached fruit. In addition, Table 4-29 shows the effect of diversity in the harvester beater's speed on the proportion of the average dislodgement of the grapefruits. It is obvious that with increase in the harvester beaters' speed from 56.50 in/sec to 73 in/sec, the grapefruit dislodgement percentage will be increased from 73.30 % to 79.72 %. Ostensibly, there are effective differences between the beaters' shaking speeds, so according to the statistical analysis, there is significant difference between the effects of the machine beaters speeds on the average of the grapefruit dislodgement percentage at the level of significance 10 %, and there is significant difference between the lowest beater's shaking speed 56.50 in/sec and the highest beater's shaking speed 73 in/sec in terms of the average percentage of grapefruit detached.

Table 4-28. The average of the detached fruit (fruits/tree).

	Beaters Shaking Speed (inch/sec)	
	56.50	73
Symbol	Shs1	Shs2
Ave. *	78[b]	95[a]
S.D.	21.11	45.32

* Averages, which have been followed by the same letter in the row, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-29. The average of the grapefruit detachment percentage (%).

	Beaters Shaking Speed (inch/sec)	
	56.50	73
Symbol	Shs1	Shs2
Ave. *	73.30[b]	79.72[a]
S.D.	11.69	17.97

* Averages, which have been followed by the same letter in the row, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of the Interaction between the Machine Forward Speeds and its Shakers Positions on the Field Harvesting

Table 4-30 illustrates the effect of interaction between the forward speeds of the harvesting machine with the shaking beaters position (beaters displacements) on the amount of the detached grapefruits. From this interaction, it was found that, the highest amount of dislodged fruit average 134 fruits/tree, resulting from interaction between the forward speed 0.62 mi/hr and the default position of the shaking beaters, while the lowest amount of detached fruits, 53 fruits/tree, was a result of the interaction between the second forward speed 1.42 mi/hr and the beaters turn buckle length at 12 inches. Also, by setting up the statistical analysis for this interaction effect, it was found that, the interactions of the ground speed 0.62 mi/hr and the default beaters position from one side, and the interactions between the ground speed 0.62 mi/hr and beaters turn buckle length at 12 inches; the ground speed 0.62 mi/hr and beaters turn buckle length at 16 inches; second ground speed 1.42 mi/hr and the default beaters position; second ground speed 1.42 mi/hr and the beaters turn buckle length at 12 inches; and the ground speed 1.42 mi/hr and the beaters turn buckle length at 16 inches, all on the other side, are considered as a clear significant influencer on the detached fruit amount, at a 90 % level of confidence. Also, the results do not show significant differences on the amount of detached fruit under the influence of the other interactions, also at 90 % level of confidence. Furthermore, from the

relative relationship between the detached fruit amount and the amount of the fruit that remained on grapefruit trees, the fruit detachment percentage is shown in Table 4-31. Table 4-31 shows the actual results of the interaction between the harvester ground speeds and its beaters' positions on the grapefruit detachment percentage. Also, as can be seen from Table 4-31, the highest average percentage of grapefruit detachment was 89.09 %, as a result of interaction between the beaters turn buckle length at 16 inches, and the lowest ground speed 0.62 mi/hr, while the interaction between the beaters at turn buckle length of 12 inches and the higher ground speed 1.42 mi/hr resulted in the lowest percentage of fruit detachment 57.75 %.

From the data results, it can be shown that, increasing the harvester forward speed from 0.62 mi/hr to 1.42 mi/hr at all the different harvesters' beaters positions resulted in a decreased percentage of fruit detachment. On the other hand, by decreasing beaters position, which means decreasing the turn buckle length from 16 inches to 12 inches at all harvester ground speeds, the average fruit detached percentage will be decreased from 89.09 % at forward speed of 0.62 mi/hr and turn buckle length 16 inches, to 57.75 %, as a result of the interaction of the forward speed 1.42 mi/hr and 12 inches turn buckle length. Statistically, it is clear that, the interaction influence of the beaters at turn buckle length 16 inches and the ground speed 0.62 mi/hr from one side, and the interactions between the first harvester ground speed 0.62 mi/hr and its beaters position at turn buckle length 12 inches; the ground speed 1.42 mi/hr and the beaters position at the default setting; and the ground speed 1.42 mi/hr and the beaters at turn buckle length 12 inches all on other side, recorded clearly as having high significant differences on the fruit detachment percentage. The other interactions were overall recorded between having and not having significant effects on each other on the proportion of the detached fruit, at level of significance 10 %.

Table 4-30. The average amount of the detached fruit (fruits/tree).

Turn Buckle Length (in)	Harvester Forward Speed (mi/hr)		Ave.
	0.62	1.42	
12	64[cd]	53[d]	59
Default Setting	134[a]	96[b]	115
16	83[bc]	88[bc]	86
Ave.	94	79	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-31. The average of the grapefruit detachment percentage (%).

Turn Buckle Length (in)	Harvester Forward Speed (mi/hr)		Ave.
	0.62	1.42	
12	66.88[be]	57.75[b]	62.32
Default Setting	84.13[ad]	74.36[dce]	79.25
16	89.09[a]	86.84[ac]	87.97
Ave.	80.03	72.98	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of the Interaction between the Beaters' Shaking Speeds and the Machine's Beaters Positions on the Field Harvesting

Influence of the interaction between various beaters positions and beaters' shaking speeds of the citrus harvester on the amount of the detached fruits is shown in Table 4-32. As can be observed in Table 4-32, with specific beaters' position determined by the turn buckle lengths at both the default setting and 16 inches turn buckle length, the number of detached fruits was increased by increasing the harvester's beaters shaking speed. It was also observed that the number of detached fruits with the turn buckle length set at 12 inches was increased by decreasing the beaters shaking speed. Moreover, the average amount of detached fruit ranged between 53 fruits/tree as a minimum average, due to the interaction of the beaters position set by turn buckle length of 12 inches and beaters' shaking speed of 73 in/sec, and 144 fruits/tree as a maximum average, due to the interaction of the beaters' shaking speed 73 in/sec, and the default beaters position. Statistical analysis found that the effect, on the amount of detached fruits, of the interaction between the highest beaters' shaking speed 73 in/sec and the beaters default position on one side, and the other side of the interactions between the other beaters' shaking speeds and harvester's beaters positions is recorded as having a high statistically significance, at 0.10 level of significance. In contrast, at level of significance 10 %, the other interactions between other beaters' shaking speeds and the beaters positions, either had or did not have a statistically significant effect on each other as measured by the amount of detached fruit. In addition, Table 4-33 refers to the influence of the interaction between the positions of the harvester's beaters and the beaters' shaking speeds on the fruit detachment percentage. From the results of the shaking speeds and beaters positions interactions, the maximum detachment percentage equals 93.54 %, using the interaction of 16 inches of the machine turn buckle length and 73 in/sec of the beaters' shaking speed, while the minimum percentage, 59.86 %, resulted from the interaction between

the beaters' shaking speed 73 in/sec and the beaters at turn buckle length of 12 inches. Also as observed, the detachment percentage of the grapefruit increased from 82.39 % to 93.54 % by increasing the shaking speed from 56.50 in/sec to the highest beaters speed 73 in/sec, at the highest beaters position at turn buckle length of 16 inches. At the lowest beaters position of 12 inches of turn buckle length, the fruit detachment percentage is decreased from 64.77 % to 59.86 % by increasing the shaking speed from 56.50 in/sec to 73 in/sec, while the interaction of the default position of the shaking beaters, and the shaking speed 73 in/sec, resulted in the fruit percentage increasing to 85.76 %. On the other hand, at both shaking speeds 56.50 in/sec and 73 in/sec, the fruit detachment percentage increased by decreasing the harvester's beaters displacement via increasing the turn buckle length from 12 inches to 16 inches. Statistically, it is clear that the interaction influence between the beaters position by the turn buckle length 16 inches and the beaters' shaking speed 73 in/sec on one side, and the beaters position by the turn buckle length 12 inches with the beaters' shaking speed 73 in/sec; the default position of the harvester's beaters with the lowest beaters' shaking speed 56.50 in/sec; and the lowest beaters' shaking speed 56.50 in/sec with the beaters position at 12 inches of the turn buckle length, all on the other side, recorded as having significant differences on the fruit detachment percentage, at the 10 % level of significance. Also, from the statistical analysis, it was clear that, there are no significant differences on the proportion of the detached grapefruits due to effect of the interactions between the other harvester's beaters positions and the beaters' shaking speeds, on each other, at the level of confidence 90 %, since there were no significant differences between the first three highest percentages of the fruit detachment, as shown in Table 4-33.

Table 4-32. The average of the detached fruit (fruits/tree).

Turn Buckle Length (in)	Beaters Shaking Speed (inch/sec)		Ave.
	56.50	73	
12	64 bc	53 c	59
Default Setting	86 b	144 a	115
16	83 b	88 b	86
Ave.	78	95	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-33. The average of the grapefruit detachment percentage (%).

Turn Buckle Length (in)	Beaters Shaking Speed (inch/sec)		Ave.
	56.50	73	
12	64.77 bd	59.86 d	62.32
Default Setting	72.73 bc	85.76 a	79.25
16	82.39 ac	93.54 a	87.97
Ave.	73.30	79.72	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of the Interaction between the Beaters' Shaking Speeds and the Machine Forward Speeds on the Field Harvesting

The data in Table 4-34 describe influence of the interaction between forward speeds of the harvesting machine with its beaters' shaking speeds on the amount of detached grapefruits. The average amount of the detached fruit ranged between the minimum amount of grapefruit 70 fruits/tree, which resulted from the interaction of the highest forward speed 1.42 mi/hr with the lowest beaters' shaking speed 56.50 in/sec, and the maximum amount of detached grapefruit at 102 fruits/tree resulted from the interaction of the lowest machine forward speed 0.62 mi/hr and the highest beaters' shaking speed 73 in/sec. The lowest average amount of the detached fruit (70 fruits/tree) was obtained using the highest forward speed 1.42 mi/hr with lowest shaking speed 56.50 in/sec. This combination did not furnish enough time to shake the whole tree canopy at a shaking time of approximately 3.88 sec/tree. In contrast, the highest average amount of detached grapefruit, 102 fruits/tree, was obtained with the lowest forward speed (0.62 mi/hr), which provided enough time to shake the whole grapefruit tree canopy, since the shaking time resulting from this speed was approximately 8.75 sec/tree. Also, it can be observed that for both beaters' shaking speeds 56.50 in/sec, and 73 in/sec, the detached grapefruit amounts are decreased by increasing the harvester forward speed from 0.62 mi/hr to 1.42 mi/hr. Similarly, at both harvester forward speeds 0.62 mi/hr and 1.42 mi/hr, increasing the beaters' shaking speed from 56.50 in/sec to 73 in/sec, results in higher detached grapefruit amounts. It is clear that, the maximum average amounts of the detached fruits were obtained by using the beaters' shaking speed 73 in/sec at both forward speeds of the harvester. From the statistical analysis, it was found that, the interaction effect between the harvester's forward speeds and the shakers' shaking speeds on the average amount of the detached grapefruits does show significant differences at the 10 % level of significance. Clearly, the interaction effect between the highest beaters' shaking speed 73 in/sec

and the lowest forward speed of the harvester 0.62 mi/hr from one side, and interaction between the lowest beaters' shaking speed 56.50 in/sec and highest machine forward speed 1.42 mi/hr, recorded as having high significant differences on the average amount of detached fruits. Besides that, there were no further significant differences between the effect of the other beaters shaking speeds and the harvester forward speeds interactions at each other on the average amount of detached fruits, also at the level of significance 10 %.

In addition, from the amounts of detached fruit and fruit remaining on the grapefruit tree canopies, Table 4-35 shows the interaction effect between the beaters shaking speeds and the machine forward speeds on the grapefruit detachment percentage. The average amount of fruit detachment percentage that resulted from this interaction ranged between 69.18 %, due to the interaction of the beaters' shaking speed of 56.50 in/sec and forward speed of 1.42 mi/hr, and 82.65 % that was the result of the interaction of the forward speed 0.62 mi/hr and the beaters' shaking speed 73 in/sec. As observed from Table 4-35, at both harvester forward speeds, the fruit detachment percentage increased by increasing the beaters shaking speed from 56.50 in/sec to 73 in/sec, while the fruit detachment percentage is decreased at all beaters' shaking speeds by increasing the harvester forward speed from 0.62 mi/hr to 1.42 mi/hr. The highest fruit detachment percentage 82.65 % is the result of the interaction between the specific forward speed 0.62 mi/hr and shaking speed 73 in/sec. This maximum percentage was obtained due to the operation at the highest shaking speed for a long enough period of time, which was acquired with the lowest forward speed 0.62 mi/hr. The forward speed 0.62 mi/hr allowed more time for the machine's shakers, to shake whole tree canopy sufficiently (8.75 sec/tree). On the other hand, the minimum fruit detachment percentage (69.18 %) resulted from the interaction between the highest forward speed 1.42 mi/hr and the lowest shaking speed 56.50 in/sec, also this percentage

occurred due to the lowest shaking speed operation with a shorter period of time. Clearly, this percentage occurred because the forward speed 1.42 mi/hr allowed less time to shake the whole grapefruit tree canopy (3.88 sec/tree).

Statistical analysis showed that, the interaction effect of the harvester's forward speeds and its beaters' shaking speeds on the percentage of detachment fruit is considered as a high contributor at the 10 % level of significance. The influence on the grapefruit detachment percentage, of the interactions between the harvester beaters' shaking speed 73 in/sec with the harvester forward speed 0.62 mi/hr, the machine forward speed 0.62 mi/hr with beaters' shaking speed 56.50 in/sec, and the machine forward speed 1.42 mi/hr with beaters' shaking speed 73 in/sec, were not a statistically meaningful on each other when the level of significance was 10 %. Similarly, the influence on the grapefruit detachment percentage, at level of significance 10 %, on the interactions between the harvester beaters' shaking speed 73 in/sec with the harvester forward speed 1.42 mi/hr, the machine forward speed 1.42 mi/hr with beaters' shaking speed 56.50 in/sec, and the machine forward speed 0.62 mi/hr with beaters' shaking speed 56.50 in/sec do not have significant differences on each other. However, the interaction influence between the lowest beaters' shaking speed 56.50 in/sec with the highest harvester forward speed 1.42 mi/hr on one side, and the highest harvester beaters' shaking speed 73 in/sec with the lowest harvester forward speed 0.62 mi/hr on the other side, has a meaningful statistical influence on the fruit detachment percentage at the 10 % level of significance.

Table 4-34. The average of the detached fruit (fruits/tree).

Forward Speed of the Harvester (mi/hr)	Beaters Shaking Speed (in/sec)		Ave.
	56.50	73	
0.62	86 [ab]	102 [a]	94
1.42	70 [b]	88 [ab]	79
Ave.	78	95	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Table 4-35. The average of the grapefruit detachment percentage (%).

Forward Speed of the Harvester (mi/hr)	Beaters Shaking Speed (in/sec)		Ave.
	56.50	73	
0.62	77.41 [ab]	82.65 [a]	80.03
1.42	69.18 [b]	76.79 [ab]	72.98
Ave.	73.30	79.72	

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

Effect of the Interaction between the Machine Beaters' Shaking Speeds, Shaking Beaters' Positions, and the Machine Forward Speeds on the Field Harvesting

The analysis which can lead to a sound decision about adjusting the harvesting machine's operational variables (harvester forward speed, beaters' shaking speed, and shaking beaters' displacement), comes from the interaction analysis done using the different operating variables. Table 4-36 shows the interaction effect between the three operating variables on the average amount of the detached grapefruits. It is observed that the detached fruit quantity ranged between 47 fruits/tree, due to the interaction between the highest beaters' shaking speed (73 in/sec), second machine forward speed (1.42 mi/hr), and the beaters turn buckle length 12 inches, and the highest detached grapefruit average amount 165 fruits/tree was obtained due to the interaction between the initial forward speed 0.62 mi/hr with the highest beaters' shaking speed 73 in/sec and the beaters at the default turn buckle length. Also, as observed from the field data, the lowest amount 47 fruits/tree may mean that the shaking time available at the highest machine forward speed (3.88 sec/tree) is significantly less than the shaking time at the lowest machine forward speed (8.75 sec/tree), and thus negatively affects fruit detachment. So, the minimum detachment is obtained due to an inadequate shaking time and shaking beaters penetration at turn buckles length 12 inches, while the maximum detachment was obtained due to sufficient shaking time and shaking beaters penetration at the default turn buckles lengths. The statistical analysis revealed that, the interaction effect between the beaters' shaking speed 73 in/sec, machine forward speed 0.62 mi/hr, and the default position of the shaking beaters from one side, and all the other harvester operation variables on the other side, on the amount of detached fruits is an arbitrary significant difference at the 10 % level of significance. Secondly, there is a significant effect, as a result of the interaction between the beaters' shaking speed 73 in/sec, machine forward speed 1.42 mi/hr, and the beaters default lengths of the turn buckle from one side, and

all the other harvester operation variables on the other side, despite the interactions between the other harvester operation variables, which provided the amount of detached fruits of 103, 95, and 86 fruits/tree, respectively, on the amount of detached fruits, also at a 0.90 confidence level. Thirdly, there is a significant difference between the interaction of the beaters' shaking speed 56.50 in/sec, machine forward speed 0.62 mi/hr, and the beaters default lengths of turn buckle from one side, and the interactions between the other harvester operation variables, which provided amount of detached fruits of 165, 59, 60, and 47 fruits/tree, respectively, from the other side, on the detached fruits amount at level of significance 10 %. In contrast, there were no significant effects found due to interaction between other operating variables of the citrus harvester on the amount of detached grapefruits at the 10 % level of significance as shown in Figure 4-10.

Additionally, the scientific decision about the appropriateness of the selected operating variables (two machine forward speeds, two beaters' shaking speeds, and three shaking beaters positions) of the original prototype of the fruit harvesting machine may be taken from the calculation results of the percentage of the detached grapefruit. Table 4-37 shows the effect of the interaction between the three operating variables (machine forward speed, beaters' shaking speed, and the harvester' beaters position) on the average amount of fruit detachment percentage. The result of that interaction reveals that the highest percentage of the detached fruit is 93.56 % as a result of interaction between the second beaters' shaking speed 73 in/sec, first machine forward speed 0.62 mi/hr, and the 16 inches turn buckle length. This high percentage of detached fruit may have resulted due to the lowest forward speed 0.62 mi/hr, which provided a sufficient shaking time to shake the whole tree canopy synchronously with an adequate shaking speed 73 in/sec. The second highest percentage of the detached fruit, 93.52 %, was a result of interaction

between the second beaters' shaking speed 73 in/sec, second machine forward speed 1.42 mi/hr, and the beaters position at 16 inches turn buckle length. This second high percentage of detached fruit may have resulted from the interaction of the highest shaking speed and more beaters penetration by the 16 inches turn buckle length, which provided a deep enough beaters penetration into the grapefruit tree canopy, with the adequate shaking speed of 73 in/sec, to shake the whole tree canopy regardless of the different shaking time due to the shaker speed. Furthermore, data demonstrates that the lowest percentage of detached grapefruit is 55.26 % as a result of interaction between the second shaking speed 73 in/sec, second machine forward speed 1.42 mi/hr, and the 12 inches turn buckle length. This lowest percentage of detached fruits may have resulted due to the maximum machine forward speed, which does not provide an enough shaking time (3.88 sec/tree) to shake the whole tree canopy, when associated with the lowest shaking beaters penetration into the grapefruit canopy (12 inches turn buckle length). As observed from the data that was obtained at both harvester's forward speeds of 0.62 and 1.42 mi/hr, and the two beaters positions of 16 inches and default turn buckles lengths, by increasing the beaters' shaking speed from 56.50 in/sec to 73 in/sec, the proportions of detached fruits increased. On the contrary, with the beaters position at 12 inches turn buckle length, at both of the harvester forward speeds of 0.62 and 1.42 mi/hr, the detachment percentage of grapefruit decreased from 69.30 % to 64.46 % and 60.24 % to 55.26 %, respectively, by increasing the shaking speed from 56.50 in/sec to 73 in/sec. Finally, the highest percentages of the detached grapefruits were obtained with the first machine forward speed 0.62 mi/hr and the second machine forward speed 1.42 mi/hr, at the maximum beaters' shaking speed 73 in/sec, and maximum beaters penetration position (16 inches turn buckle length).

Statistically, there are significant differences for the interaction effects between the forward speed 0.62 mi/hr, beaters' shaking speed 73 in/sec, and the 16 inches turn buckle length (third beaters' position) from one side, and the interactions between the other harvester operation variables, which provided the percentages of the detached grapefruits of 69.30, 67.14, 64.46, 60.24, and 55.26 %, from the other side, on the detached fruit percentage at level of significance 10 %. Similarly, the interaction effects between the forward speed 1.42 mi/hr, beaters' shaking speed 73 in/sec, and the 16 inches turn buckle length (third beaters' position) from one side, and the interactions between the other harvester operation variables, which provided the percentages of the detached grapefruits of 69.30, 67.14, 64.46, 60.24, and 55.26 %, from the other side, on the detached fruit percentage at the 10 % level of significance. Also, there are obvious significant differences for the interaction effects between the forward speed 0.62 mi/hr, beaters' shaking speed 73 in/sec, and the beaters position at the default lengths of the harvester's turn buckles (second beaters' position) from one side, and the interactions between the other harvester operation variables, which provided the percentages of the detached grapefruits of 69.30, 67.14, 64.46, 60.24, and 55.26 %, from the other side, on the percentage of detached grapefruit at the 10 % level of significance. Also, there are noticeable differences from the effect of the interaction between the forward speed 0.62 mi/hr, beaters' shaking speed 56.50 in/sec, and the 16 inches turn buckle length (third beaters' position) on one side, and the forward speed 0.62 mi/hr, beaters' shaking speed 73 in/sec, and beaters position at turn buckle length of 12 inches; the forward speed 1.42 mi/hr, shaking speed 56.50 in/sec, and the beaters position at turn buckle length of 12 inches; and the forward speed 1.42 mi/hr, shaking speed 73 in/sec, and the first beaters at 12 inches turn buckle length, all from the other side, on the fruit detachment percentage at the 10 % level of significance. Finally, there were no significant effects found by

the other operating variables interactions on the fruit detachment percentage as shown in Figure 4-11.

In conclusion, should be noted that for both harvester forward speeds 0.62 and 1.42 mi/hr, in increasing the beaters penetration into tree canopy from 12 inches to 16 inches at both shakers' speeds 56.50 in/sec and 73 in/sec, have favorable interactions of grapefruit detachment percentages. So, the sound decision from the final-test results as shown in Table 4-37, is operating the new prototype of a self-propelled over the top citrus harvesting machine using canopy shaker at both harvester forward speeds 0.62 and 1.42 mi/hr, beaters' shaking speed 73 in/sec, and beaters position at 16 inches turn buckle length, where 93.56 % and 93.52 % maximum grapefruit detachment percentages were obtained.

Table 4-36. The average of the detached fruit (fruits/tree).

Turn Buckle Length (in)	Harvester Forward Speed (mi/hr)				
	0.62 (Mfd1)		1.42 (Mfd2)		
	Canopy Shakers Speed (in/sec)		Canopy Shakers Speed (in/sec)		
	56.50 (Shs1)	73 (Shs2)	56.50 (Shs1)	73 (Shs2)	Ave.
12 (Bp1)	69^{cde}	59^{ce}	60^{ce}	47^{e}	59
Default (Bp2)	103^{bd}	165^{a}	70^{cde}	123^{b}	115
16 (Bp3)	86^{bce}	81^{cde}	80^{cde}	95^{bc}	86
Ave.	86	102	70	88	
Shakers Speed	78		95		
Harvester Speed	94		79		

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

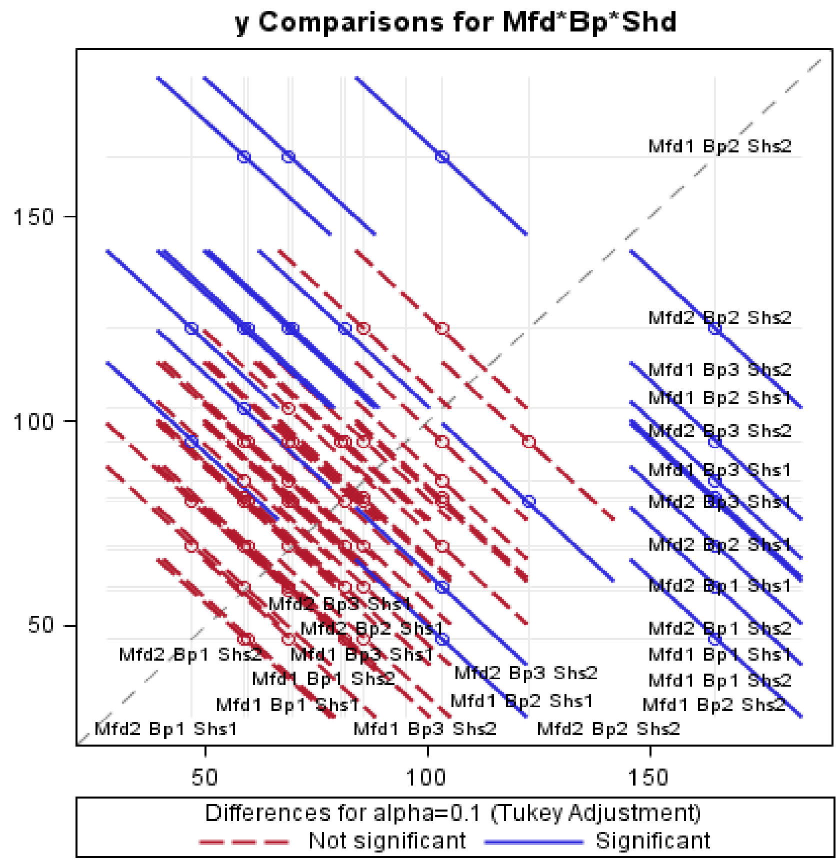

Figure 4-10. Comparison results for the effect of the interaction between the three operating variables on the amount of the detached grapefruit (fruits/tree).

Table 4-37. The average of the fruit beads detachment percentage (%).

Turn Buckle Length (in)	Harvester Forward Speed (mi/hr)				
	0.62 (Mfd1)		1.42 (Mfd2)		
	Canopy Shakers Speed (in/sec)		Canopy Shakers Speed (in/sec)		
	56.50 (Shs1)	73 (Shs2)	56.50 (Shs1)	73 (Shs2)	Ave.
12 (Bp1)	69.30^{bcd}	64.46^{cd}	60.24^{ce}	55.26^{c}	62.32
Default (Bp2)	78.32^{abde}	89.94^{a}	67.14^{bcd}	81.58^{ad}	79.25
16 (Bp3)	84.62^{ab}	93.56^{a}	80.17^{abde}	93.52^{a}	87.97
Ave.	77.41	82.65	69.18	76.79	
Shakers Speed	73.30		79.72		
Harvester Speed	80.03		72.98		

Averages, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

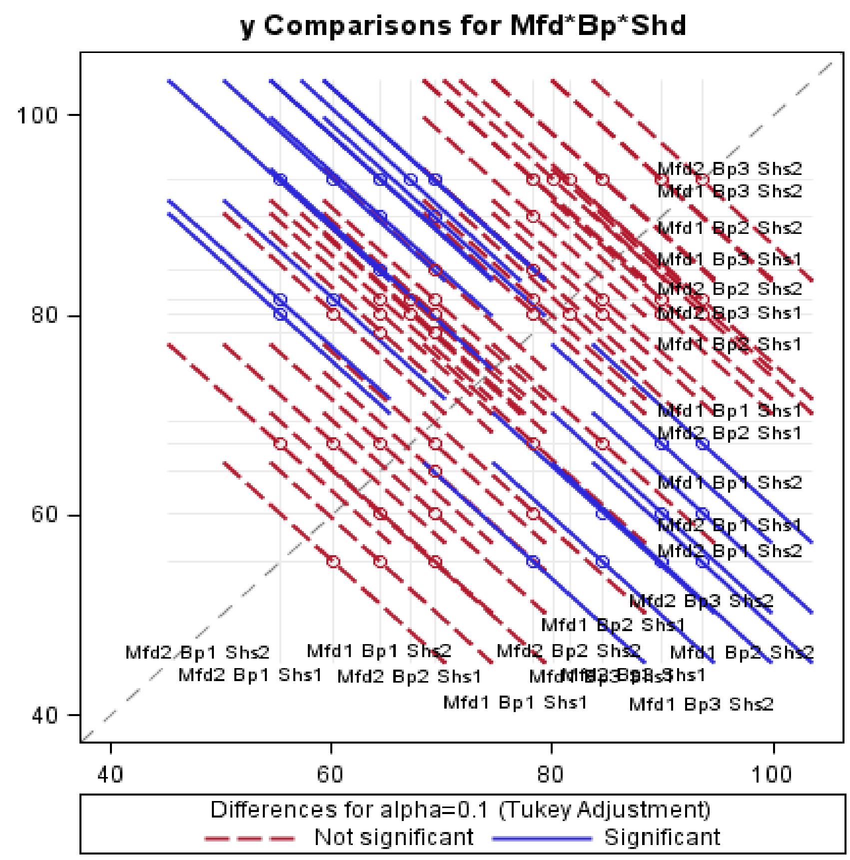

Figure 4-11. Comparison results for the effect of the interaction between the three operating variables on the grapefruit detachment percentage (%).

Effect of Length of the New Canopy Shakers on the Citrus Harvesting

Additional experiments on the final prototype of the citrus harvester were carried out on January 15, 2014, to investigate the effect of additional beaters, which were attached to the final shaker design along with the original main beaters, on the grapefruit detachment rate. These tests were conducted with a beater length longer than the beaters length utilized for the final field experiments (i.e., experiments of the January 6, 2014). The new beaters (extra-long beaters) were 48 inches long, while the previous extra beaters had a length of 30 inches (Figure 4-12). The machine operating variables that were used for this test were, harvester's forward speeds of 0.62 mi/hr as a slow speed and 1.87 mi/hr as a fast speed, the shakers' shaking speed of 63.74 in/sec (the two flow control valves were set on number 3), and the beaters penetration was constant at 16 inches for each turn buckle length. The shaking results are presented as shown in Table 4-38.

Table 4-38 shows the effects of the forward speeds of the final harvesting machine design (additional final-test) on the amount of the grapefruits that were harvested from the fruit tree and the fruit detachment percentage. Practically, it was found that, the average amount of detached grapefruit decreased from 89 fruits/tree to 70 fruits/tree, and the fruit detachment percentage decreased from 93.29 % to 92.89 % by increasing the harvester forward speed with the extra-long beaters. Consequently, by operating the canopy shaker harvesting machine with either the harvester's forward speed 0.62 mi/hr (as a slow speed) or 1.87 mi/hr (as a fast speed), 63.74 in/sec shakers' shaking speed, the beaters penetration at 16 inches turn buckle length, and the extra-long beaters, yielded an equivalent fruit detachment percentage as was realized by operating the machine with either forward speed 0.62 mi/hr or 1.42 mi/hr, 73 in/sec shakers' shaking speed, beaters penetration at 16 inches turn buckle length, and the extra short beaters (93.56 % and 93.52% respectively). By applying statistical analysis to the field data as shown in Table 4-38 by the small letters, it was found that with 10 % level of significance, there is an

obviously significant difference between the influence of the low and high forward speed on the amount of detached grapefruits, while there is no significant difference at the 10 % level of significance, for the influence of the harvesting machine forward speeds, and the length of the new extra beaters, on the average percentage of the detached grapefruits.

In fact, it is possible to obtain a higher detached grapefruit percentage, more than 93.29 %, by utilizing the harvester with forward speed 0.62 mi/hr, 63.74 in/sec shakers' shaking speed, and 16 inches turn buckle length. The experimental result shown in Table 4-38 (replicate number 3) has affected the final average of the detached grapefruit percentage, due to fact that the tree canopy size (wide and height of canopy) was greater than the dimensions of the internal harvesting tunnel of the shaking machine (69 × 104 inches). Almost all of the tree branches were strong branches that could not be shaken by the shakers, and almost all of the grapefruit remaining in the tree canopy were found at the central top of the canopy and lower part of the grapefruit tree canopy.

Figure 4-12. The Final harvester’s shaking beaters (new extra-long shaking beaters). [Photo courtesy of Naji Al-Dosary]

Table 4-38. The averages of the detached grapefruits (fruits/tree) and the grapefruits detachment percentage (%).

Shaking Speed (Flow Control No. 3)	Replicated Treatments	Harvester Forward Speed (mi/hr)			
		Slow 0.62		Fast 1.87	
		Detached Fruits (Fruits)	Fruit Detachment Rate (%)	Detached Fruits (Fruits)	Fruit Detachment Rate (%)
High Shaking Speed 63.74 (in/sec)	1	97	98.98	55	98.21
	2	75	97.40	66	77.65
	3	108	72.97	72	96
	4	67	97.10	77	97.47
	5	99	100	78	95.12
Ave.		89[a]	93.29[a]	70[b]	92.89[a]
S.D.		17.36	11.42	9.45	8.60

* Averages, which have been followed by the same letter in each two similar columns, do not have significant differences among them statistically at a 0.90 confidence level.

Distribution of Acceleration Magnitude in the Grapefruit Tree Canopy

Two experiments of acceleration distribution were conducted on grapefruit trees, to evaluate the final prototype citrus harvesting machine with 13 beaters on each shaker unit. Fifteen USB accelerometer sensors (model X16-1C) were placed at various branches locations in the tree canopy (Ray Ruby grapefruit). The same trees were used as these shaken in the summer harvest of 2013, with sensors at approximately the same locations. The acceleration magnitude data (g) for the X16-1C sensors were recorded at a sample rate of 50 Hz and sample size 30,000 (counts). The results of the distribution of the acceleration during the shaking were obtained using a constant beaters penetration of 12 inches turn buckle length, high beaters' shaking speed 63.74 in/sec, slow machine forward speed, and the harvester's tunnel width fixed at 69 inches.

Shaking Acceleration Distribution for the Final Design of the Shaking Beaters on One Grapefruit Canopy

The results of Table 4-39 show the maximum magnitude of the acceleration (g) and the average magnitude of each acceleration period (g) that were gained by operating the harvester's beaters on one grapefruit tree canopy (0.97 mph average of the harvesting machine speed) where 15 sensors were attached in the grapefruit tree canopy. The distribution of the acceleration upon shaking operation was non-uniform with differences in the magnitudes of the acceleration as shown in Figure 4-13. The branches behavior was changed along the tree canopy perimeter (laterally and vertically). The maximum magnitude average was 15.253 g. The maximum magnitude was achieved by the left beaters squad on the left side of the grapefruit tree, while the maximum magnitude recorded by the right beaters squad on the right side of the grapefruit tree was equal to 11.35 g. At the top of the tree canopy, the maximum magnitude average was recorded between 4.427 g, caused by the left beaters squad, and 8.138 g, caused by the right beaters squad. The minimum magnitude average (4.063 g) was recorded at the lower central part

of the canopy near the trunk (Figure 4-13). The acceleration (g) has a higher maximum magnitude (15.253 g) at the left and right side of the tree perimeter (40 inches to 65 inches above ground), than the branches at the central top of the tree canopy (8.138 g). Generally, comparison results based on the sensors location, showed that the acceleration magnitude was substantially higher (average, 9.791 g) at the lower branches on the tree canopy (up to 40 inches to 65 inches from the ground) than the branches at the central top of the tree canopy (average, 6.867 g), or the limbs along the central band of the tree canopy and trunk (4.158 g was average of sensors 3 and 15). Also, the average magnitude of the acceleration (g) increased distinctly when moving from inside the tree canopy to the perimeter of the canopy.

Table 4-39. A precise average magnitude of the acceleration (g) among the tree canopy branches, depending on the delimited accelerometer sensors locations, and the final machine operating variable into one tree canopy.

No. of Accel. Sensor	Accelerometer Sensors Locations			Branch Dia. at the Posted Sensor (in)	First Trial (12 inches of turn buckle linkage)	
	Into the Tree Canopy	From Main Trunk (in)	From Ground (in)		Ave. of the Max. Accel. Mag. (g)	Ave. Accel. at each Shaking Period (g)
1	Right central edge, Top, Back	20	75	0.93	6.468	1.373
2	Right central edge, Top, Front	16	75	0.85	7.933	1.373
3	Central trunk, Down	6	32	2.50	4.063	1.154
4	Left edge, Top, Back	36	58	0.90	11.661	2.002
5	Back edge, Right	31	50	0.75	6.211	1.532
6	Central edge, Top, Left, Back	16	62	1.42	4.636	1.209
7	Left edge, Front	22	41	0.65	13.344	2.183
8	Central edge, Top, Left, Front	8	72	0.73	7.369	1.461
9	Central edge, Top, Left, Back	30	75	0.93	4.427	1.294
10	Right edge, Front	31	40	0.95	11.35	1.744
11	Right central edge, Front, Top	37	72	0.87	8.138	1.715
12	Left edge, Back	33	43	0.78	15.253	2.440
13	Left edge, Top	15	58	0.70	6.088	1.411
14	Left edge, Front	24	36	0.92	10.01	1.624
15	Central edge, Back, Down, Rear of the main trunk	20	27	0.90	4.252	1.222
Ave. (g)					8.080	1.582
S.D. (g)					3.537	0.376

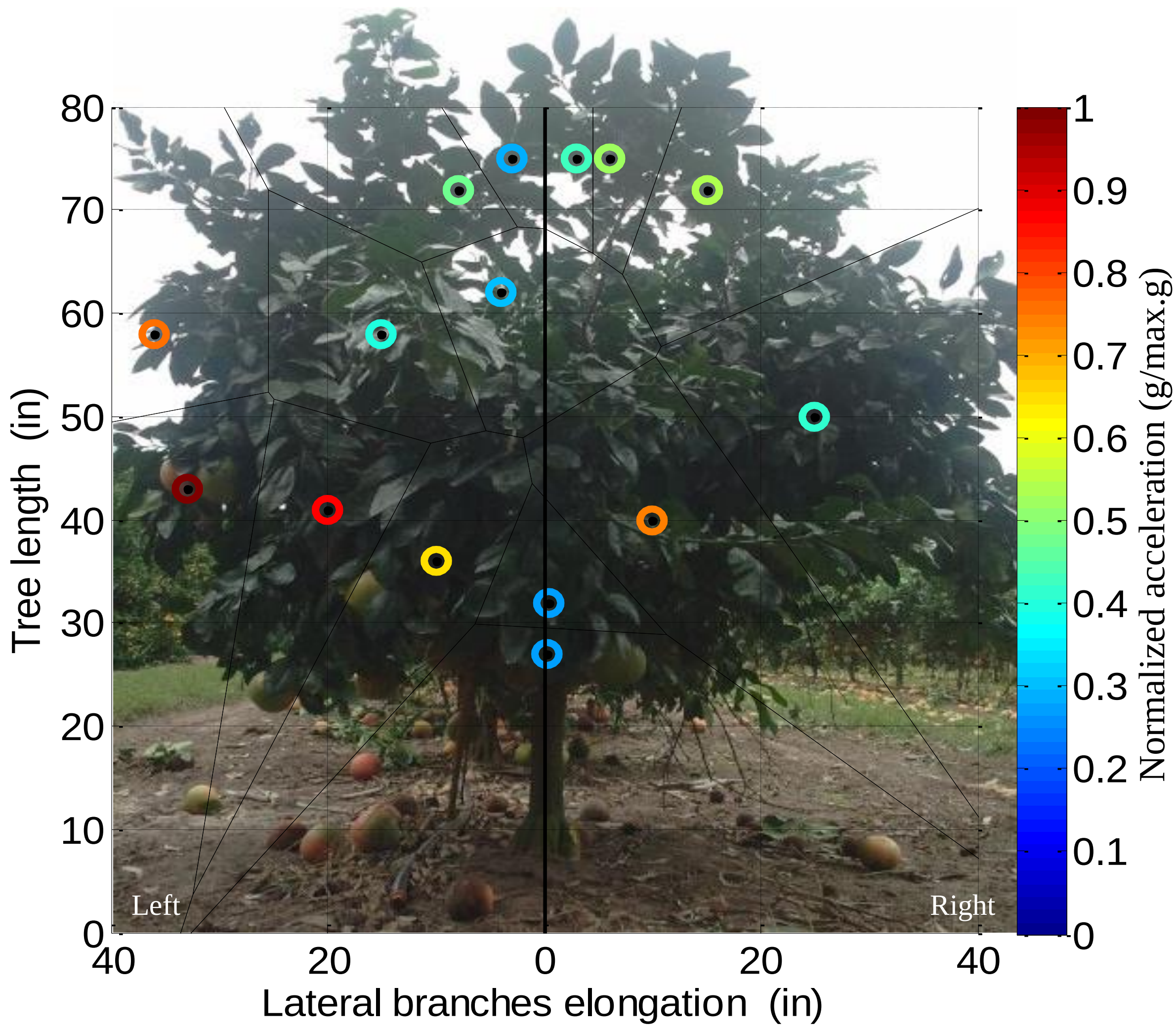

Figure 4-13. Acceleration magnitude distributions into one grapefruit tree canopy by the highest beaters shaking speed (front view). [Photo courtesy of Naji Al-Dosary]

Acceleration Distribution by the Final Design of the Shaking Beaters into Three Harvested Grapefruit Canopies

For this experiment, 15 USB accelerometer sensors (model X16-1C) were placed on various branches at different locations on three random tree canopies (Ray Ruby grapefruit), where 5 sensors were attached to each individual tree canopy. The results of the acceleration magnitude distribution in the tree canopies were obtained by various shaking speeds of the harvester's beaters as referenced in Table 4-40. The results of Table 4-40 show the average maximum magnitude of the acceleration (g), and the average magnitude of each acceleration period (g), that were achieved by operating the shaking beaters on three different grapefruit canopies (0.85 mph of machine forward speed, 12 inches turns buckles length, beaters' shaking speed of 63.74 in/sec). The distributions of acceleration upon shaking the trees canopies were uneven as shown by the diversity in the magnitudes of the acceleration (g) in Figure 4-14. As was observed, the tree branch behavior changed along each tree canopy perimeter (laterally and vertically). The maximum average of the acceleration magnitude was 14.09 g, which was obtained at the left side of the tree perimeter using the left shakers, and the minimum magnitude average was 6.27 g, at the right side of the tree perimeter using the right shakers. At the top of the tree canopy (more than 52 inches above the ground), averages of the maximum magnitude were recorded between 6.270 g and 10.34 g. The averages of the maximum magnitude at the lower tree canopy, that is less than 52 inches from the ground, were recorded between the values of 7.152 g and 14.09 g. Also, the maximum acceleration magnitude is increased from the center of the tree canopy (average of 6.928 g) to the grapefruit tree perimeter (average of 9.80 g). The lowest sensor on the grapefruit canopy (sensor number 3, 15 inches rear of the main trunk) showed 7.544 g as the maximum magnitude, while the highest sensor (sensor number 7) on the top of the tree canopy showed 6.367 g maximum acceleration magnitude. In general, as shown in

Figures 4-14, the comparison results, depending on the sensors locations, showed that the shaking beaters acceleration magnitude was substantially higher at the lower branches on the tree canopy (55 inches from the ground and less) than the branches on the central top of the tree canopy, or the limbs on central band of the tree canopy (sensor 3). At the lateral branches (height of 40 inches and more from the ground), the left side of the tree canopy had more acceleration magnitude (Ave. of 9.366 g) than the right side (Ave. of 8.249 g).

Finally, from the two field experiments of the shaking acceleration effect, the differences in the acceleration magnitude distribution from the left and right shakers may have occurred due to a pair of variables: the misadjustment of the two flow control valves, causing the two operated crank-shafts to lack the same rotational speed, or the harvester's operator not maintaining center of the machine harvesting track (the main trunk of the grapefruit tree was not centered). Statistically, the total averages of the maximum acceleration magnitude, that are shown in the Tables 4-39 and 4-40, confirmed that there was no significant difference, at the 10 % level of significance, for the influence of the shaking trials, (one tree canopy or various grapefruit trees canopies, at a high shaking speed of the harvester's beaters) on the average amount of the acceleration magnitude of the tree's branches.

Table 4-40. A precise average magnitude of the acceleration (g) among the tree canopy branches, depending on the delimited accelerometer sensors locations, and the final machine operating variables at three different tree canopies.

No. of Trees	No. of Accel. Sensors	Accelerometer Sensors Locations			Branch Dia. at the Posted Sensor (in)	First Trial (12 inches of turn buckle linkage)	
		Into the Tree Canopy	From Main Trunk (in)	From Ground (in)		Ave. of the Max. Accel. Mag. (g)	Ave. Accel. at each Shaking Period (g)
1	1	Left edge, Front	36	43	0.83	13.08	2.278
	2	Central edge, Left, Top	6	70	0.60	7.114	1.609
	3	Central edge, Back, Down	15	29	0.91	7.544	1.358
	4	Right edge, Down	16	34	1.41	7.152	1.708
	5	Central edge, Right, Top, Back	12	53	0.65	7.297	1.501
2	6	Left edge, Back	32	47	1.00	14.09	2.414
	7	Central edge, Left, Top	3	75	0.95	6.367	1.666
	8	Right edge, Top, Back	20	62	0.63	10.34	1.819
	9	Right edge, Top, Back	25	53	0.75	8.932	1.752
	10	Right edge, Front	17	52	0.58	6.270	1.342
3	11	Left edge	20	47	0.81	9.003	1.752
	12	Central edge, Left, Front	15	54	0.75	6.308	1.517
	13	Left edge, Back	24	40	0.87	9.603	1.782
	14	Right edge	16	40	0.86	9.718	2.051
	15	Central edge, Right, Top	8	65	1.20	6.938	1.679
Ave. (g)						8.651	1.749
S.D. (g)						2.647	0.307

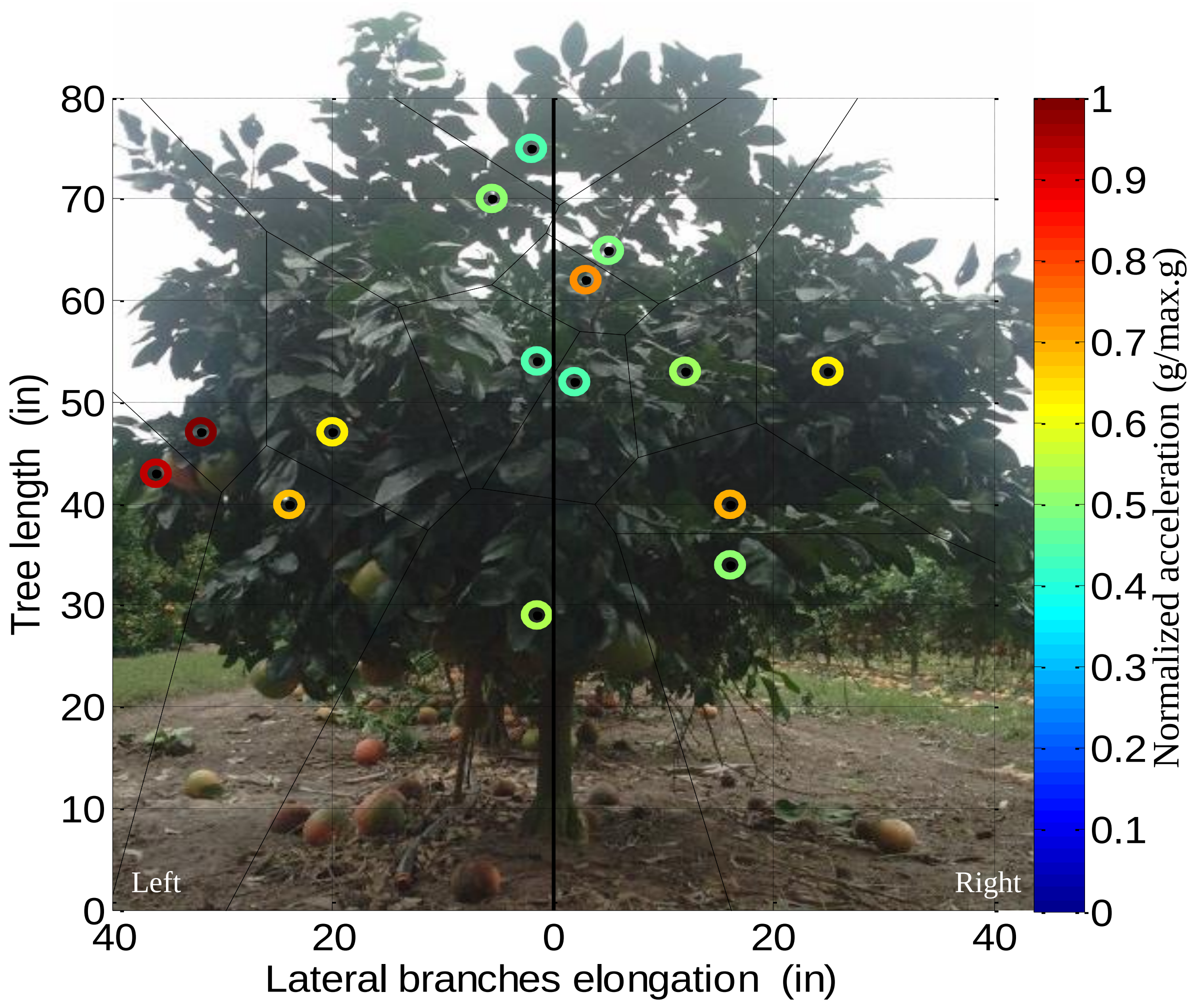

Figure 4-14. Acceleration magnitude distribution into three diverse grapefruit trees canopies by the highest beaters shaking speed (front view). [Photo courtesy of Naji Al-Dosary]

CHAPTER 5
COMPARISON RESULTS DEPENDING ON THE IMPROVEMENT OF THE SHAKING SHAKERS DESIGN

The shaker design of the citrus canopy shaking machine was improved from the original 7 beaters per shaking unit to 13 beaters per shaking unit in the fall of 2013 (Figures B-6 and B-7). It was felt that increasing the number of beaters would have a significant effect on the efficiency of the harvester machine, where the more beaters penetrating into the tree canopy, the more engagement with the tree branches, and fruit. This turned out to be a significant improvement in fruit detachment efficiency.

Effect of the Harvesting Machine Forward Speed on the Field Harvesting

Figure 5-1 shows effects of the forward speed of the two canopy shaker designs on the average percentage of the detached grapefruit. From the two field trials at low forward speed, it was found that, increasing the beaters number will increase the detached grapefruit percentage from 29.54 % to 80.03 %. Also, using the harvester's highest forward speed showed that, by decreasing the beaters number, the detached grapefruit percentage will be decreased from 72.98 % to 18.71 %. So, the modification of increasing the number of beaters from 14 beaters to 26 beaters, with altered beater material, increased the average percentage of fruits detachment from 24.13 % to 76.51 %. In general, the two shaker unit designs showed similar results, that by increasing the harvester forward speed, the detached grapefruit percentage will be decreased. Statistically, it was found that with 10 % level of significance, there is an obviously significant difference between the influences of the two shaker units' designs with the harvesting machine forward speeds on the percentage of the detached grapefruits.

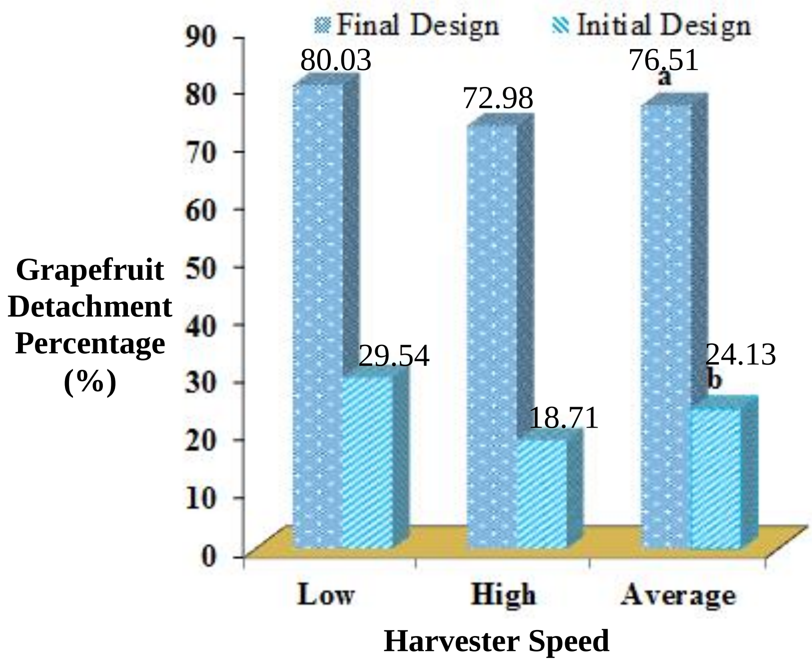

Figure 5-1. Effect of the changing in the shakers design with the shaking machine speed on the grapefruit detachment percentage.

Effect of the Beaters and Tree Canopy Engagement on the Field Harvesting

The effect of varying the harvester's beater position either by changing the turn buckle length or by changing the harvester tunnel width is showing in Figure 5-2. Figure 5-2 shows that for the preliminary shakers design, the percentage of grapefruit detachment is increased from 23.64 % to 27.31 % by increasing the beater's penetration into the grapefruit tree canopy. The final shakers modification reveals that increasing the beater's penetration into the grapefruit tree canopy increased the grapefruit detachment percentage from 62.32 % to 87.97 %. In addition, by increasing the beater's penetration into the tree canopy, the final shakers design gave higher grapefruit detachment percentage (76.51 %) than the preliminary shaker design (25.48 %). In general, the two shaker units' designs have agreed that by increasing the harvester's beater penetration into the grapefruit tree canopy, the detached grapefruit percentage will increase. According to the statistical analysis at the 10 % level of significance, it was found that, there is a

visible significant difference of the final shakers modification on the fruits detachment percentage (%).

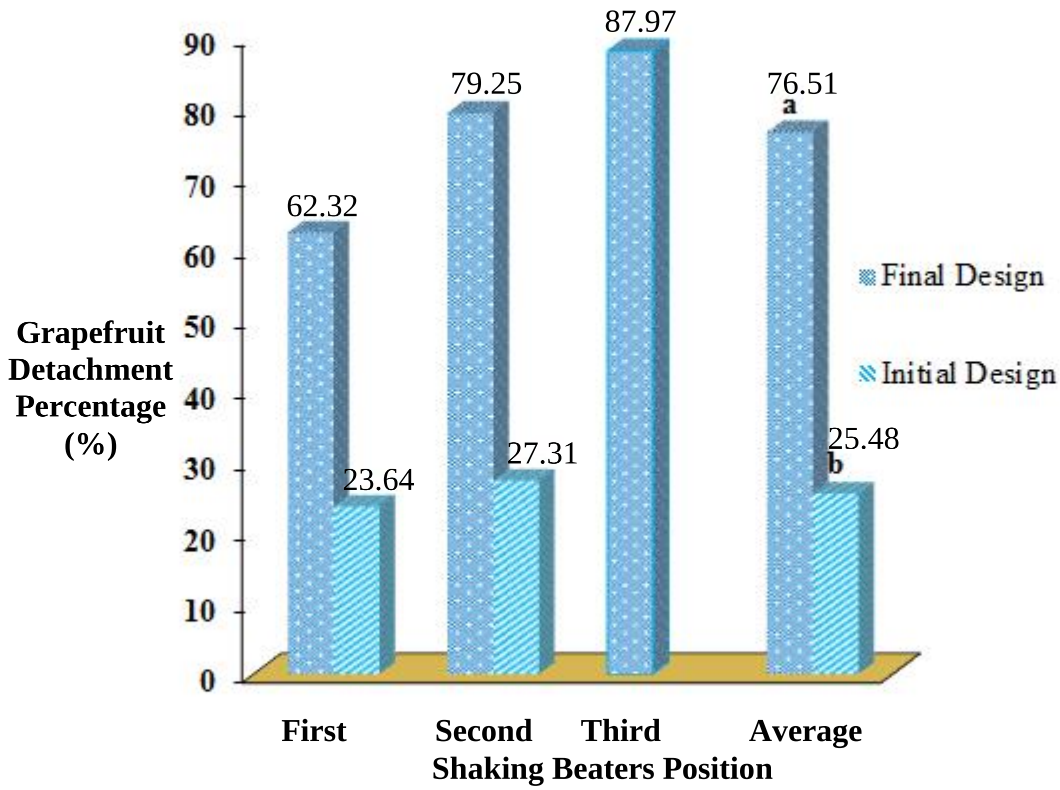

Figure 5-2. Effect of the changing in the shakers design with the shaking beaters position on the grapefruit detachment percentage.

Effect of the Harvester's Beater Shaking Speed on the Field Harvesting

In terms of the harvester's beater speed influence, Figure 5-3 displays the influence of the two machine beaters design (14 beaters and 26 beaters) on the average grapefruits detachment percentage. By increasing the beaters shaking speed (with the first design), the fruits detachment percentage is increased from 17.90 % to 35.77 %, and similarly, the final shakers design provides fruit detachment percentage between 73.30 % and 79.72 % when the shaking speed increased. Also, at all shaking speeds, by increasing number of beaters from 14 to 26 beaters, the average grapefruit detachment percentage increased from 26.62 % to 76.51 %, respectively. Generally, when the beaters' shaking speed is increased from low speed to high shaking speed,

the average amount of the grapefruit detachment percentage is increased as the final and initial shakers design had agreed. From the statistical analysis at the 10 % level of significance, it was found that, there is a significant difference between the influences of the two shaker designs in terms of the average amount of grapefruits detachment.

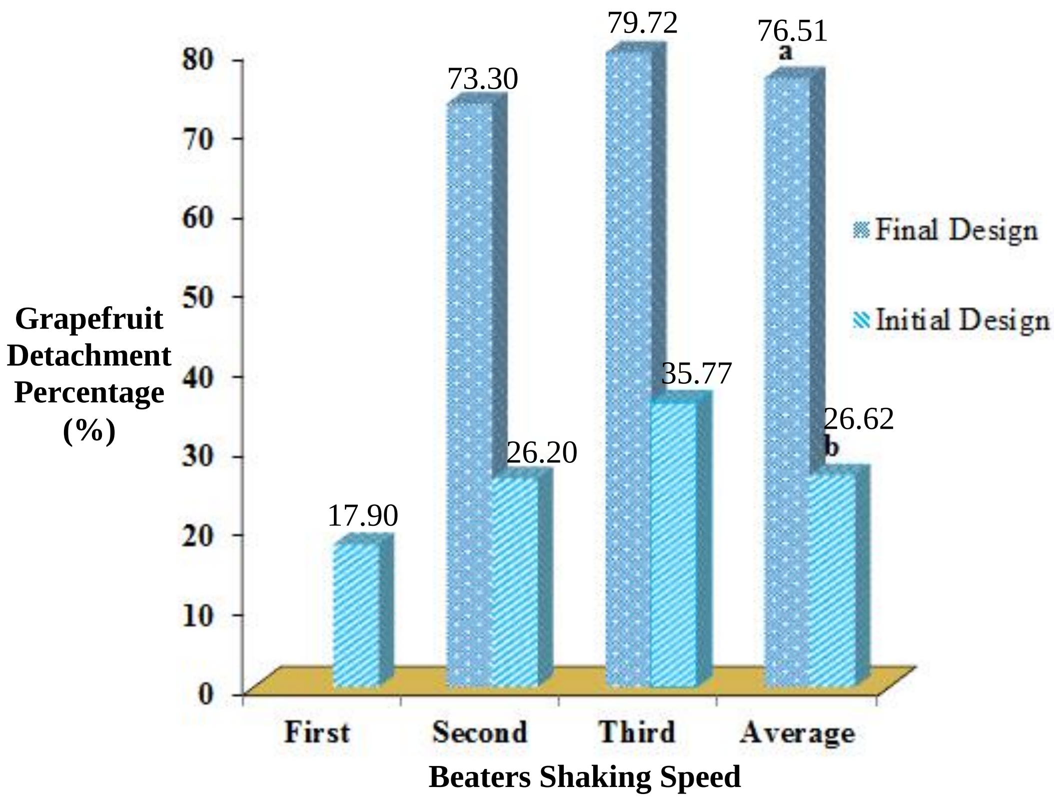

Figure 5-3. Effect of the changing in the shakers design with the shaking speed on the grapefruit detachment percentage.

Effect of the Machine Beaters Number on the Citrus Canopy Shaker Harvesting Machine Efficiency

Obviously, Figure 5-4 shows that the highest fruit detachment percentage (by individual tree) was achieved by increasing the number of the shaking beaters. The maximum average of fruit detachment percentage using the preliminary design of the shaker (14 beaters) was 41.58 %, while the final shaker design (26 beaters) provided a maximum average fruit detachment percentage of 93.56 %. During the preliminary shaker design operation, the two highest

detachment percentages were obtained by the lowest machine forward speed with different beater shaking speeds, however, using the final shaker design, the two highest fruit detachment percentages were obtained with the same beaters shaking speed, but via both the lowest and highest harvester forward speeds. Finally, from the statistical analysis, it was found clearly that, there is a significant difference, due to effect of the 14 beaters of the initial harvester design and the 26 beaters of the final harvester design on the citrus canopy shaker harvesting machine efficiency, at the level of confidence 90 %.

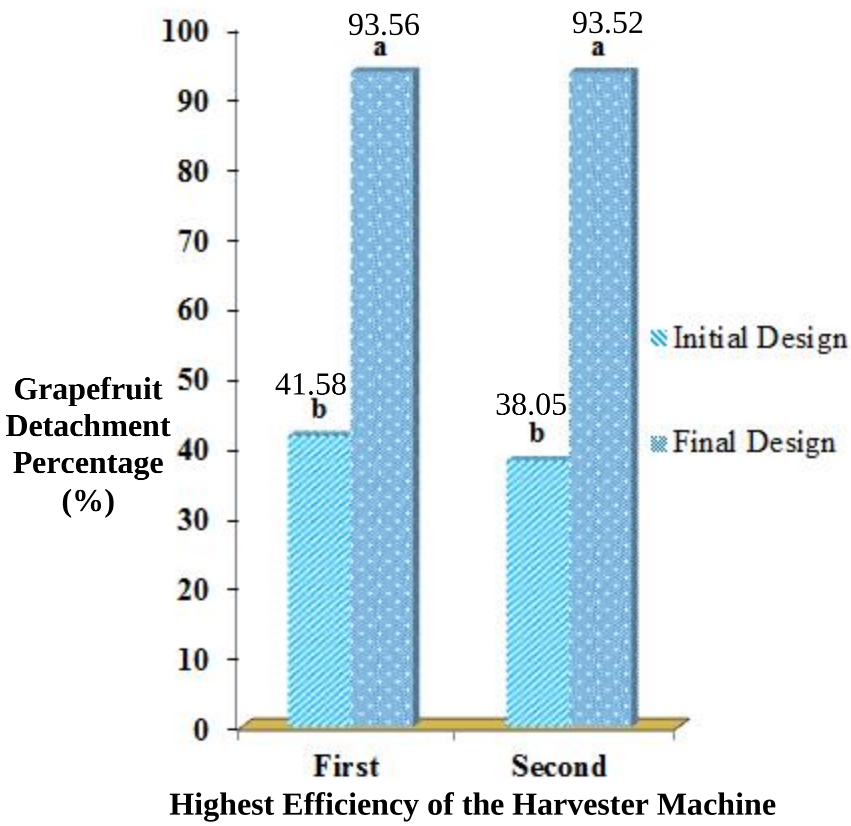

Figure 5-4. Final effect of the changing in the shaker design on the grapefruit detachment percentage (the highest and second highest detachment percentage).

Acceleration Magnitude Distribution on the Grapefruit Tree Canopy by the Two Shaker Designs

Comparison results were taken from an experiment using the 15 USB accelerometer sensors that were attached on various branches on three grapefruit trees canopies, with 5 sensors mounted on diverse branches on each canopy. The results of the acceleration magnitude distribution on the tree canopies were obtained by operating the shaking beaters at high shaking speed (65.90 in/sec for preliminary design and 63.74 in/sec for final design), penetration into random three grapefruit trees canopies were determined by 12 inches length of the turn buckles for the beaters, and 69 inches of internal tunnel width for the harvester machine. Figure 5-5 shows that, the highest acceleration magnitude (14.09 g) was obtained by the final shaker design using 26 beaters, while in contrast, the initial design of the canopy shaker, with 14 beaters, provided 8.00 g as a maximum magnitude value. Also, the minimum value of the acceleration magnitude by the final design (6.27 g) was still substantially more than the minimum acceleration magnitude that was obtained by the initial shaker design (1.93 g). Evidently, by increasing the number of shakers on each canopy shaker unit from 14 beaters to 26 beaters, the average of the acceleration magnitude increased from 5.04 g to 8.65 g, as shown in Figure 5-5. Statistically, the small letters in Figure 5-5 confirm that, there is an obvious significant difference, at the 10 % level of significance, between the influence of the initial and final canopy shaker design on the average of the maximum acceleration magnitude on the grapefruit tree branches, and thus more effective shaking of grapefruit tree canopies will result.

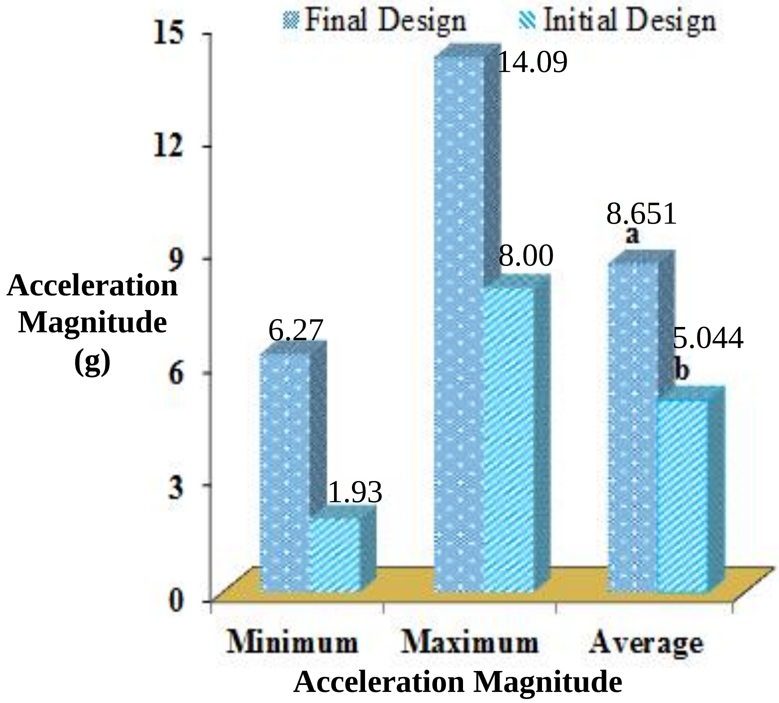

Figure 5-5. An acceleration magnitude result on the grapefruit tree canopy by operating the two shaker models with a high beater shaking speed.

CHAPTER 6
ECONOMIC ANALYSIS OF THE NEW CANOPY SHAKER MACHINE

The Economic Performance

A preliminary analysis of the economic influence of the citrus harvesting machine performance, and the resulting harvesting efficiency, were used to estimate the effect on citrus fruit harvesting cost, previously shown in Table 3-5. The outputs of Table 3-5 show several economic variables of the harvester operations, which may affect the result of the harvesting costs. For the economic calculation in this study, some potential economic impacts from the operation of the new citrus harvester were estimated hypothetically such as: the citrus harvester capacity, yearly operated hours, the harvester life, the yearly harvested area, and the harvester's purchase price and maintenance. So, by operating the new harvester prototype for citrus harvesting, the harvester cost will be decreased significantly by increasing either the harvester efficiency or the fruit recovery rate. Therefore, by applying the recommended operation variables (i.e., harvester forward speeds 1.42 or 0.62 mi/hr, and the default harvesting width 69 inches), and 94 % of the fruit detachment percentage, which would be obtained by operating the final citrus tree canopy shaker design with an attached catch frame (effectively delivering almost 100 % of the detached fruit to the accompanying trailer), to the equation 3-33, the total cost of this harvester operation as shown by the results in Table 3-5 was estimated as 152.38 $/hr for the final canopy shaker design. To emphasize the result of equation 3-33, Table 6-1 displays the anticipated harvesting cost of the mechanical harvester and two trucks, per hour, by applying the coefficients in Table 3-5 to determine the estimated costs of the new mechanical harvester and trucks (i.e., ownership (fixed) and operating costs (variable)). So, from Tables 6-1, the total cost of the new citrus harvesting concept is calculated as 151.17 $/hr as well as the labor cost is 1.66

$/box. The field efficiency, which includes the exact harvesting time, and the time that lost during the harvester adjustment and movement between orchard lines, is estimated to be 70 %.

Through the operational development of building a new more efficient citrus harvester, mechanical harvesting has the further economic advantage of higher productivity. The new prototype of citrus canopy shaker, operated at either low or high forward speed, was estimated to harvest approximately 366 to 800 boxes per hour, respectively. This estimate applies with 70 % field efficiency and 94 % fruit recovery via an attached catch frame which will deliver almost 100 % of the detached fruit to an accompanying truck, as shown in Table 6-2. Also, the new prototype of citrus canopy shaker was estimated to shake and harvest, when operated at the recommended operating settings, between 293 and 641 trees per hour when the field efficiency is 70 %. So this new design, as well as other mechanical harvesters, will decrease the field labor cost and intensity impact. The innovative canopy shaker is expected to harvest between 1.47 and 3.29 acres per an hour, with one harvester operator and two truck operators, resulting in a harvest cost of 151.17 $/hr. Also, from Table 6-3, the total grapefruit mechanical harvesting cost by the new mechanical shaker is expected to range between 260.64 and 340.28 $/acre, with the machine recovery 94 % and 70 % field efficiency. Subsequently, if the harvest rate is 238 box/acre, 94 % fruit recovery, and 70 % field efficiency applies, the predictable cost of each grapefruit box will be between 0.72 and 0.94 $/box, while the grapefruit manual harvesting cost is 1.66 $/box. Accordingly, grapefruit yield harvested by the new mechanical harvester (366-800 box/hr) was found to be between 36 and 80 times greater than the productivity of manual harvesting (8-10 box/hr, Futch et al., 2005). This result is consistent with the reduced cost of citrus fruit harvest, by more than 50 %, which has referred by Brown, 2005. Also, as the mechanical harvesting can improve the labor productivity from 8 to 10 box/hr to more than 30 box/hr (Futch et al., 2005),

the entire harvesting time by mechanical harvesting seems to be decreased to as little as one-third (1/3) of the manual harvesting time. Also, from Table 6-3, the total mechanical harvesting cost, for each orange box, by the new mechanical canopy shaker is expected to be between 0.55 and 0.73 $/box, if the harvest rate is 494 box/acre, when the orange recovery is 94 % and 70 % field efficiency, while the manual harvesting cost is estimated as 1.99 $/box. In general, continuing with the machine improvement may present a desired result of decreasing the mechanical harvesting cost.

Table 6-1. Estimated costs of the ownership (fixed) and operation (variable).

Hourly Costs of the Mechanical Harvester with two trucks		
Classification		Cost
Fruit detachment rate by the machine (%)		94.00
Grapefruit field yield of the season 2013-2014 (box/acre)		362
Ownership price ($)		250,000.00
Life-expectancy (years)		10.00
Yearly operation hours (hr/year)		873
Salvage value ($)		20,000.00
Fixed costs	Depreciation ($/hr)	26.35
	Interest ($/hr)	10.54
	Tax ($/hr)	17.90
	Insurance ($/hr) (i.e., 0.25% of purchase price/873)	0.72
Total relevant fixed ownership cost ($/hr)		55.51
Variable cost	Fuel expense ($/hr)	2.41
	Lubrication ($/hr)	0.98
	Maintenance ($/hr)	57.27
	Harvester operator wage ($/hr)	15
	Truck operator wage ($/hr)	10 × 2
Total relevant variable cost ($/hr)		95.66
Total expense of the new mechanical harvester ($/hr)		151.17

Table 6-2. Estimated the unit costs ($/box) of the new mechanical harvester.

Classification		Expected Cost	
		Grapefruit	Orange
Harvester cost ($/hr)		151.17	
Fruit recovery (%)		94.00	
Field efficiency (%)		70.00	
Predicted number of trees in intended orchard (trees/acre)		272	375
New mechanical harvester performance			
Field yield (box/acre)		362	750
Average productivity of the grapefruit orchard (fruits/tree)		113	
Field yield (box/tree)		1.33	2
If the field efficiency 100 (%)	Harvester low speed (trees/hr)	418	
	Harvester high speed (trees/hr)	915	
	Harvester low speed (box/hr)	556	747
	Harvester high speed (box/hr)	1216	1712
	Harvester low speed (acre/hr)	1.47	
	Harvester high speed (acre/hr)	3.29	
If the field efficiency 70 (%) and 94 (%) fruit recovery	Harvester low speed (box/hr)	366	491
	Harvester high speed (box/hr)	800	1126
Expected cost to repair grove included repairing of the irrigation system, tree pruning and skirting ($/acre)		80.00[1]	
Harvest cost ($/box)	By harvester low speed (0.62 mi/hr)	0.41	0.31
	By harvester high speed (1.42 mi/hr)	0.19	0.13
Orchard service cost ($/box)		0.22	0.11

Table 6-3. Comparison of harvest cost: new mechanical harvester versus manual harvesting.

Method			Expected Cost ($/box)	
			Grapefruit	Orange
The New Mechanical Harvester with Fruit Recovery 94 % and Efficiency 70 %	Harvester cost	By harvester low speed	0.41	0.31
		By harvester high speed	0.19	0.13
	Orchard repairing cost		0.22	0.11
	6 % fruit gleaning with roadsiding charge		0.21	0.21
	Debris cost		0.10[2]	0.10[2]
	Total mechanical harvesting cost		0.72 – 0.94	0.55 – 0.73
The Hand Harvesting when Fruit Recovery 100 (%)		Fruit picking	0.71[3]	1.008[3]
		Fruit roadsiding	0.95[3]	0.989[3]
	Total manual harvest cost		1.66	1.997

[1]Roka et al., 2009; [2]Roka, 2010; and [3]Muraro, 2012.

Observations of the Grapefruit Orchard Damages

Grapefruit Orchard Damages by the Preliminary Canopy Shaker Design

The harvester's shaking beaters, which deliver the shaking motion to the tree canopy, is the major source of canopies damages (Figure 6-1). The beaters' shaking speed was essential to the efficiency of fruit harvesting.

The beaters' design (i.e., 7 round metal pipes and flexible PVC pipes on each shaker unit, as shown in Figure 6-2) helped to minimize the tree canopy damages. The rounded design allowed the trees' branches to slip up or down when the branches and beaters collide. However, branch splits have occurred as a result of entanglement of inflexible branches in the lower canopies, especially branches with crotch angles, with the harvester's lowest beaters (Figure 6-3). Also, the tree canopies with non-uniform (non-concentric) shapes were another source of branch damages, where split branches occurred on one side of the canopies at each trial. So, as the trunks of the grapefruit trees were inclined toward one side more than the other, the canopies were extended farther horizontally on one side than the other. As a result, the harvester's operator could not take the main trunk of the grapefruit tree as the center of the harvesting direction, which resulted in injuries to the trees branches by the canopy shaking machine.

Generally, canopy shaking caused many leaves to drop off the tree, yet without excessive tree defoliation, especially during longer durations of shaking time. During the harvesting trials, some leaves were dropped as seen in Figure 6-4. Also, as observed, the main tree trunks were unaffected by the shaking beaters, so there were no visible injuries to them, and not many grapefruits near the trunk had fallen. Also, despite these issues, after harvesting trials by the preliminary machine design (pre-test trials) were completed, the grapefruit trees seem to be in perfect health (Figure 6-5). Thus, this result will help to reduce the required field maintenance cost.

Figure 6-1. The preliminary citrus harvesting machine during its operation. [Photo courtesy of Naji Al-Dosary]

Figure 6-2. The preliminary harvester’s shaking beaters (the green part is a solid round steel pipe and the gray part is a flexible round PVC pipe). [Photo courtesy of Naji Al-Dosary]

Figure 6-3. Some injured branches due to the shaking beaters' treatment. [Photos courtesy of Naji Al-Dosary]

Figure 6-4. Tree defoliation due to the shaking beaters' treatments on May 2013. [Photo courtesy of Naji Al-Dosary]

Figure 6-5. Grapefruit trees after the May 2013 harvesting trials seem to be in good health. [Photo courtesy of Naji Al-Dosary]

Grapefruit Orchard Damages by the Final Canopy Shaker Design

Additional development of the citrus harvesting machine included-attaching extra beaters (30 inches of a flexible 1 inch (OD) UHMW polyethylene white pipe) to the main beaters (25 inches of curved steel pipe and 30 inches of a flexible 1 inch (OD) UHMW polyethylene white pipe) on the two shakers systems of the preliminary shaker design. The result was the harvester's shaking beaters delivered more shaking acceleration to the tree canopy. So the consequence of operating the 26 beaters of the final design at a fixed tunnel width of 69 inches may have been the main cause of the canopies branch damages as shown in Figure 6-6. Furthermore, the main beaters' design (i.e., curved metal pipes with attached UHMW polyethylene white pipes shown in Figure 6-7) could have helped minimize the tree canopy damages. However, as stated previously, some grapefruit canopy splits occurred due to some inflexible branches in the lower tree canopy as shown in Figure 6-8. The first beater at the bottom of each shaker unit is 28 inches above the ground, exactly where the strong lower branches of the trees canopies (almost 2.50 inches of diameter) were located. So as observed, the trees trunks were unaffected by the shaking beaters, but two trees, out of the total trees tested with the improved harvester, had trunks broken at the base as shown in Figure 6-8. These breaks may have occurred because the main trunk of each tree was divided laterally into two strong crotches that could not avoid the strong beating by the lowest shaking beater. Another possible cause for the broken trunks may have been the lowest right beater on the right shaker unit (operator's right hand) impacted the right trunk crotch when the harvester's operator unintentionally missed the main trunk alignment with the central track of the harvester. This incident could have been resolved if a catch frame had been attached underneath the harvester's shakers, centering main trunk on the main track. According to the harvesting results, 27 trees out of 70 treated trees had a broken crotch branch (large branch) on at least one side of the tree canopy. The broken branches diameters ranged between 0.65 and 2.15

inches. The broken branches concentrated inside the trees canopies between 26 and 58 inches above the ground. Additionally, 16 trees out of the 70 treated trees had at least one small sub-branch broken at one side of the tree canopy, or both sides (Figure 6-9). Rarely, some tree branches received bark damage (Figure 6-10). Furthermore, as previously described, canopy shakers can cause many leaves to drop off the tree without excessive tree defoliation, especially during longer duration shaking times, so during the harvesting trials some leaves had been dropped, as shown in Figure 6-11, and some grapefruits had dropped with their stems (Figure 6-12). Also, after harvesting trials were completed, the irrigation system in the field seems to have been unaffected by the shaker machine (Figure 6-13). This result will also help to reduce the required field maintenance cost.

Obviously, the damages to tree branches and trunks of the non-uniform canopies, and crotches splitting, can be resolved by proper utilization of the hydraulic system to control the machine internal tunnel width, and the resulting shaking beaters penetration into the tree canopy, as well as establishing a new load level and body suspension system that will be developed for the shaking beaters vertical height mechanism.

Finally, to showcase the operation and the optimal performance of the prototype of an innovative, self-propelled over the top citrus harvesting machine using canopy shakers, the Object 6-1 shows the video of the canopy shaking machine's operation in grapefruit orchard during the season of 2013-14 harvest trials, while the video in Object 6-2 shows the harmonization of the shaking speed of the harvester's beater design.

Object 6-1. Video of innovative citrus canopy shaker performance (.mp4 file 10.4MB)

Object 6-2. Video of harvester's beaters harmonic shaking speed (.mp4 file 6.46MB)

Figure 6-6. The final citrus harvesting machine during its field operation in the winter of 2014. [Photo courtesy of Naji Al-Dosary]

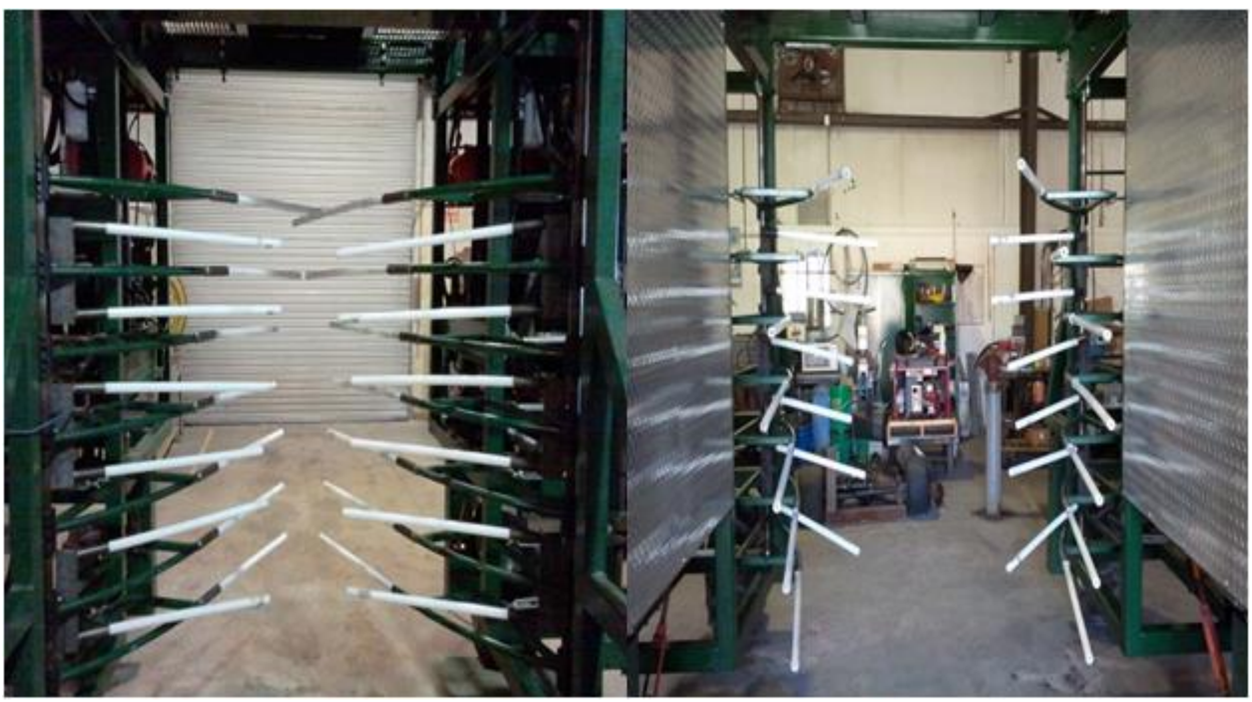

Figure 6-7. The Final harvester's shaking beaters (the green part is a solid round steel pipe and the gray part is the flexible UHMW polyethylene white pipe at the default position). [Photos courtesy of Naji Al-Dosary]

Figure 6-8. Broken trees occurred unintentionally due to moving the shaking machine in a zigzag where the trees’ trunks had beaten by the lowest shaking beater. [Photos courtesy of Naji Al-Dosary]

Figure 6-9. Some injured branches due to treatment of the new shaking beaters. [Photos courtesy of Naji Al-Dosary]

Figure 6-10. Bark damage occurred on some branches due to treatment of the new shaking beaters. [Photo courtesy of Naji Al-Dosary]

Figure 6-11. Tree defoliation due to January 2014 treatments of the improved shaking beaters. [Photo courtesy of Naji Al-Dosary]

Figure 6-12. Some grapefruits with their stems due to treatment of the new shaking beaters. [Photo courtesy of Naji Al-Dosary]

Figure 6-13. Grapefruit trees irrigation system after the harvesting trials. [Photo courtesy of Naji Al-Dosary]

The Harvesting Process May Have Been Affected by the Field Conditions

As has been observed from the field experiments with the two machine shakers designs, there are many reasons for the disparity of results of either the detachment percentage of the harvested fruit or shaking distribution of the harvester's beaters on tree canopies. It may have occurred due to the misadjustment of the flow control valve between both harvester units (two operated crank-shafts) resulting in different rotational speeds of the beaters, the accuracy of the harvester's operator in maintaining the center of the machine harvesting track with the main trunk of the grapefruit tree, or due to the grapefruit tree shape, which may not have had a concentric and homogenous vegetation canopy. Homogenous canopy was defined as those trees that had been trimmed and skirted to clear trunk and lower branches to 24 to 30 inches (height of the grapefruit canopy off the ground), but in practice, some sides were 15 to 40 inches (Figures 6-14 and 6-15). However, as shown in Figure 6-16, some trees had their trunks distorted and inclined toward one side more than the other side, thus the grapefruit canopies were extended horizontally to one side more than the other side.

Tree canopy pruning may have also affected grapefruit detachment percentages. The canopy pruning was completed before harvesting time. Pruning underneath the tree canopy resulted to the grapefruits dangled down close to the ground (the lowest beaters were 25 inches above ground for the preliminary design and 28 inches for the final design test). Thus, almost all of those grapefruits close to the ground were out of the shaking beaters range as shown in Figures 6-17 and 6-18. Also, variability in average yield per grapefruit tree (78 fruits per tree for the preliminary harvester test and 113 fruits per tree for the final test) may have been the main reason affecting the total grapefruit detachment rate.

Finally, in terms of the observed injuries to the grapefruit trees, splits have occurred to some canopy branches as a result of the branches entanglement with the harvester's beaters and

operating the two machine designs on the internal harvesting width of 69 inches. In other words, this injury (splits) occurred due to the engagement of the solid part (metal) of the shaking beaters with the branches underneath the grapefruit canopies, especially the branches with large woody crotch angles.

Figure 6-14. Uniform grapefruit tree canopy involved by the harvesting machine tunnel of the final design. [Photos courtesy of Naji Al-Dosary]

Figure 6-15. Heterogeneous grapefruit tree canopy forced by the internal tunnel of the final shaking machine design. [Photos courtesy of Naji Al-Dosary]

Figure 6-16. Some misshapen grapefruit trunks. [Photos courtesy of Naji Al-Dosary]

Figure 6-17. Grapefruits hanging down close to the ground due to the tree canopies pruning of summer 2013. [Photos courtesy of Naji Al-Dosary]

Figure 6-18. Grapefruits hanging down close to the ground due to the tree canopies pruning of winter 2014. [Photos courtesy of Naji Al-Dosary]

Future Studies of the New Representative Citrus Canopy Shaker Modification

The citrus harvesting concept that was used in this research employed two shaking beaters units (one each on the left and right side of the machine) to reap the citrus fruit from tree canopy. Movement is transferred to the shaking beaters through the use of the crank-shaft, where the rotational motion is translated to linear motion by the turn buckles, which then transfers the motion to the harvester's beaters. The new prototype of citrus harvesting machine consists of two main systems: the machine hydraulic system and the shaking beaters. The machine hydraulic system also consists of four main hydraulic circuits: transmission to drive the harvester wheels, retracting and extending of the internal tunnel width of the harvester, steering system, and the shaking beaters speed hydraulic system. In addition, the tree canopy shaking system had a pair of 7 shaking beaters and a pair of 6 additional beaters on each side, which received their movement from the crank-shaft. Accordingly further development that can be done to improve the harvesting efficiency of the new canopy shaker design is indicated in the following practical points:

1- Investigate the operator safety during the machine field operations is inevitable.

2- Establishing new load level and body suspension systems where the two flange bearings of each beaters-pivot shaft (beaters-holder) are fixed on the machine body to obtain better penetration of the mechanical removal units (harvester's beaters) into citrus tree canopy, and to shake the adjacent fruit that may be hanging by stems underneath the canopy. This can be accomplished by building a new flexible frame, with its hydraulic system, to hold only the mechanical removal units (the shaking beaters), or building a new suspension system on each wheel frame to manage the height of the citrus harvester from the ground, which will assist in increasing the beaters penetration without retracting or expanding the entire machine body.

3- Modifying the harvester's beaters to be strong enough to avoid the fatigue, which may have been the result of employing the PVC pipe or the UHMW polyethylene white pipe, or adding more extra beaters on each beaters-holder shaft to increase shaking that should be transferred to the citrus tree canopies. Also, the short sleeve rod that was used to join the solid part and the PVC pipe or the UHMW polyethylene pipe of the shaking beaters to the metal beaters part should be taken into consideration. Also, proper shielding to cover the two shaft units, and employing proper eccentric shafts instead of the used

crank-shafts on the machine may provide a smoother beaters shaking speed with more safety to the harvester handlers. Each eccentric shaft has an eccentric bearing (e.g., two eccentric bearings) attached to the drive-shaft (motor shaft) instead of having the cranks at equal distances, which may have caused to the harvester's beaters to vibrate when it spins (i.e., a rotary shaft with an eccentric bearings).

4- Retest the prototype of harvesting machine after the new amendments to assess the optimal performance under the citrus field conditions or by operating this new prototype with a chemical application especially the citrus abscission agent CMNP.

Consequently, by modifying some anticipated parts, the machine's operation would be obviously enhanced. In addition as a following phase, by attaching a new catch frame with conveyor belts to this new citrus canopy shaker, the harvesting time will be maintained.

CHAPTER 7
CONCLUSION

In this research study, the effectiveness of a new prototype citrus harvesting machine, which shakes trees by surrounding the tree canopies with two shaking units, was studied on high density dwarf trees conditions. Operationally, the harvester beaters were thrust into the tree canopies to different depths, depending on the turn buckles' length. Three sets of operating variables were studied: two different beaters shaking speeds, three various positions of the machine's shaking beaters, and two forward speeds of the canopy shaker machine for the final performance test. Experiments were carried out on a field of grapefruit at the Plant Science Research and Education Center in Citra (PSREC), which is located 20 miles southeast of the city of Gainesville, Florida. The harvesting times were May and June 2013, the fruit of season 2012-2013, for the pretest of the preliminary design, and the harvesting time for the final design experiments was January 6th and 15th of 2014 during the fruit of season 2013-2014. The fruit under this study were the variety Ray Ruby grapefruits. Also, the average yield of the grapefruit field during the 2012-2013 season was 55,143 fruits/hectare (78 fruits/tree), while the 2013-2014 season yielded 76,020 fruits/hectare (113 fruits/tree). The results of testing the two prototypes of the canopy shaker machine on citrus tree harvesting are listed in the following sections.

The effect of the varying the forward speeds on the harvester field performance was shown by different fruit harvest yields. By increasing the harvester forward speed, the average percentage of detached grapefruits decreased from 29.54 % to 18.71 % with the preliminary design and from 80.03 % to 72.98 % with the final design. Increasing the harvester forward speed reduced the required canopy shaking time. Operating at higher forward speed, the preliminary design averaged 4.30 sec/tree, and the final design averaged 3.88 sec/tree. Operating

at the machines lower speed increased total shaking time for the preliminary design to an average 6.49 sec/tree, and final design shaking time also increased to 8.75 sec/tree.

For the effect of the internal harvesting tunnel width and the shaking beaters penetrations on the harvester field performance, increasing the swath width of the preliminary design from the default width 69 inches to 75 inches leads to a decrease in the percentage of fruits detachment from 27.31 % to 23.64 %. The reason for that decrease may be that the machine is working at swath width greater than the lateral width of the trees canopy, or the operating width did not provide enough penetration depth for the machine's beaters, which in turn decreased the amount of detached fruits. By increasing the turn buckle length on the final design machine, the grapefruit detachment percentage increased from 62.32 % to 87.97 %. The reason for that increase may have been that the machine was operating with greater penetration of the shaking beaters into the grapefruit tree canopies.

The effect of the beaters' shaking speed on the field performance of the two canopy shaking machine designs showed that with an increase in the harvester's shaking speed increased performance. With the preliminary shakers design, an increase in shaking speed from 40 to 73 in/sec resulted in an increase in detached grapefruit from 17.90 % to 35.77 %. In the final design, with an increase in shaking speed from 56.50 to 73 in/sec, the percentage of the grapefruit detachment increased from 73.30 % to 79.72 %.

In general, as it was calculated, the maximum percentage of the detached grapefruits when operating the preliminary shakers design was 58.06 %, as a result of interaction between the first beaters' shaking speed of 40 in/sec, first machine forward speed of 0.90 mi/hr, and first harvesting tunnel width of 69 inches. Operating the final shakers design with different parameters, resulted in several 100 % detached grapefruits harvests. On the other hand, the

highest average of detached grapefruit by the preliminary citrus canopy shaker design was 41.58 %, as a result of interaction between the third beaters' shaking speed of 73 in/sec, first machine forward speed of 0.90 mi/hr, and harvester's tunnel width of 75 inches. Moreover, the highest average grapefruit detachment percentage by the final citrus canopy shaker design were 93.52 %, as a result of interaction between the beaters' shaking speed of 73 in/sec, high machine forward speed of 1.42 mi/hr, and beaters position at turn buckle length of 16 inches; and 93.56 %, as a result of interaction between the beaters' shaking speed of 73 in/sec, machine forward speed of 0.62 mi/hr, and beater turn buckle length of 16 inches. Also, operating the final design with the extra-long beaters provided grapefruit detachment percentage equal to 93.29 %, as a result of interaction between the beaters' shaking speed of 63.74 in/sec, machine forward speed of 0.62 mi/hr, and beaters position at turn buckle length of 16 inches.

As observed from the preliminary harvester design performance, the distribution of the shaking vibrations in the tree canopy was uneven with large diversity in the magnitudes of the acceleration. So depending on the sensors location, by increasing the beater penetration into the grapefruit tree canopy from 10 to 12 inches, the average magnitude of the acceleration on trees branches increased from 3.40 to 3.85 g. Also, by increasing the beaters' shaking speed from 45.30 in/sec to 65.90 in/sec, the average magnitude of the acceleration (g) on the grapefruit tree's branches was increased from 3.65 g to 5.04 g. In addition, when operating the final harvester design, the average of the magnitude of the acceleration (g) on the grapefruit trees' branches were 8.08 g, when the harvester machine operated at the forward speed of 0.97 mi/hr, 12 inches turn buckle length, and 63.74 in/sec beaters shaking speed; and 8.651 g, when the harvester machine operated by the forward speed 0.85 mi/hr, 12 inches turn buckle length, and 63.74

in/sec beaters shaking speed. It was also observed that the acceleration magnitudes were more evenly distribution in the final design performance.

The number of laborers in the citrus fields has been reduced by using the mechanical harvesting approaches over manual harvesting (CCSC requires 6 laborers while TSC requires 3) (Roka et al., 2009). With this new prototype self-propelled canopy shaker machine, the desired goal is to have one harvester operator and two fruit transport operators.

In conclusion, a self-propelled over the top citrus harvester for high density citrus was developed, which achieved fruit detachment percentage of 94 % on average and as high as 100 % fruit removal on some trees. Consequently, this study recommends, operating the new prototype citrus harvesting machine at either forward speed 0.62 mi/hr or 1.42 mi/hr, with turn buckle length 16 inches, and beaters' shaking speed 73 in/sec. These configurations resulted in higher grapefruit detachment percentage, with average 94 %. Although, the initial prototype does not have a catch frame and material handling system, these results are very encouraging for the future of high density citrus mechanical harvesting. Granted these results were based on grapefruit rather than orange, but these results demonstrate the potential. In addition, although some limited tree damages did occur during testing, they were minimal, and it is believed that with better shielding and shaker head control, the damage can be reduced even further. In this study, operational parameters were identified which improved harvest performance and form the basis for future harvesting trials. There are numerous opportunities for improvement, but this work has demonstrated concept feasibility.

APPENDIX A
HYDRAULIC SYSTEMS

Hydraulic Control Systems of the Innovative Continuous Canopy Shaker harvesting Machine

The developed citrus canopy shaking machine as mentioned in chapter three typically includes three effective hydraulic control systems; the hydraulic control system for the canopy shaker's travel speed, the hydraulic control system for the beaters shaking speed, and the hydraulic control system for the harvesting tunnel width of the canopy shaker. So, the fulfilled components of the harvesting machine hydraulic systems are presenting in the following figures.

The Hydraulic Control System of the Beaters Shaking Speed

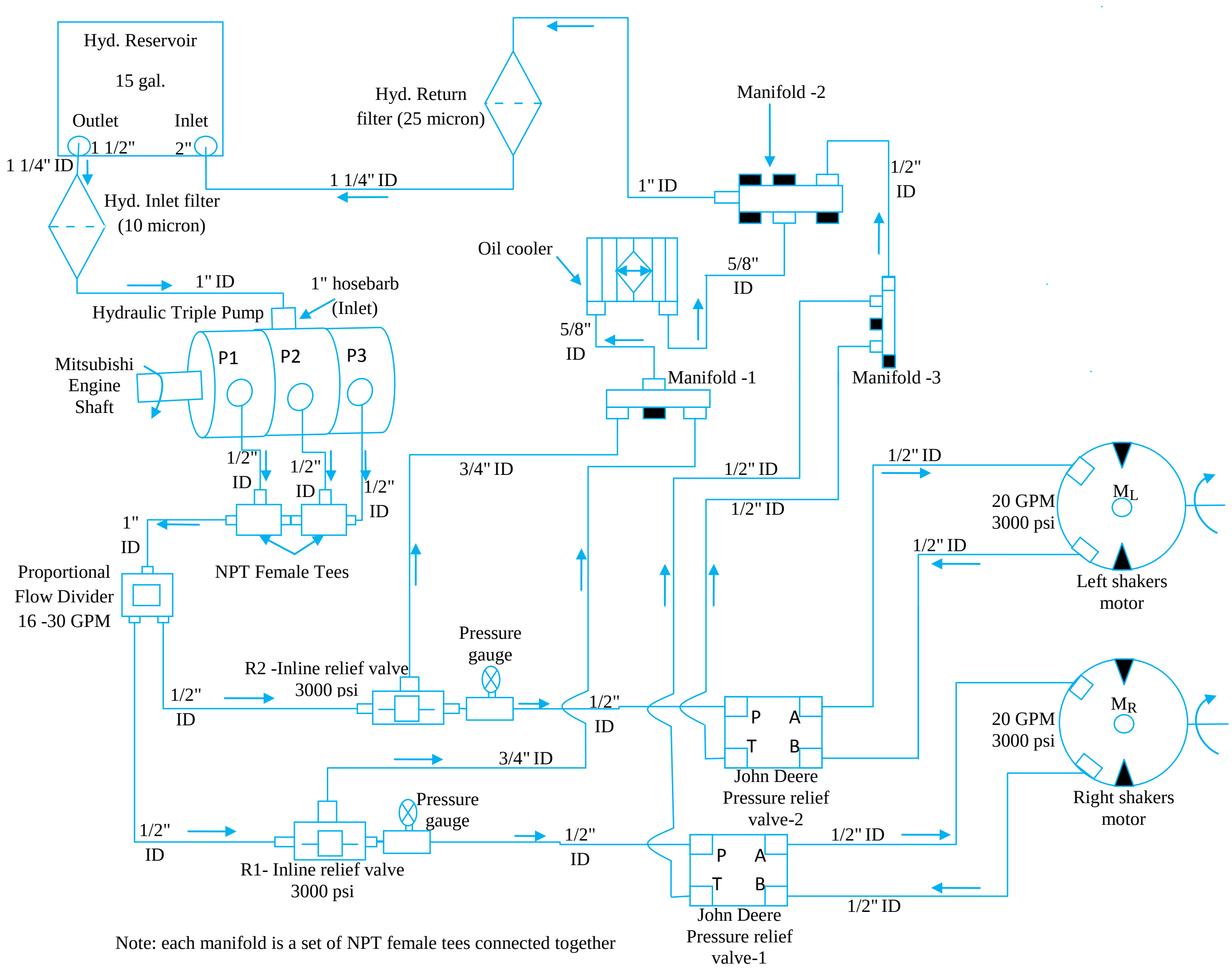

Figure A-1. Major components of the hydraulic system of the two canopy shakers units.

The Hydraulic Control System of the Canopy Shaker's Travel Speed (Preliminary Design)

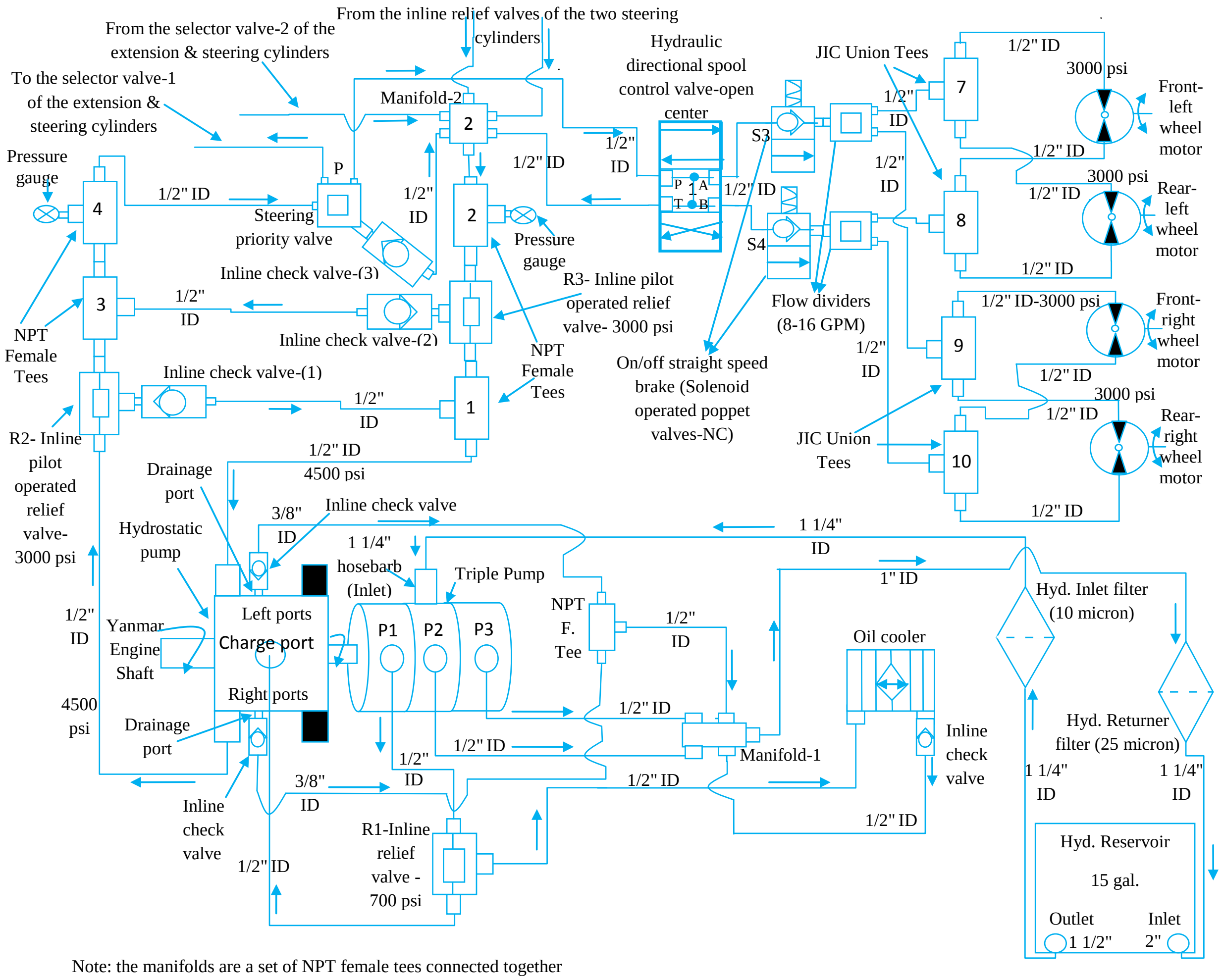

Figure A-2. Major components of the hydrostatic drive of the preliminary self-propelled shakers machine.

The Hydraulic Control System for the Harvesting Tunnel Width of the Canopy Shaker and the Steering System (Preliminary Design)

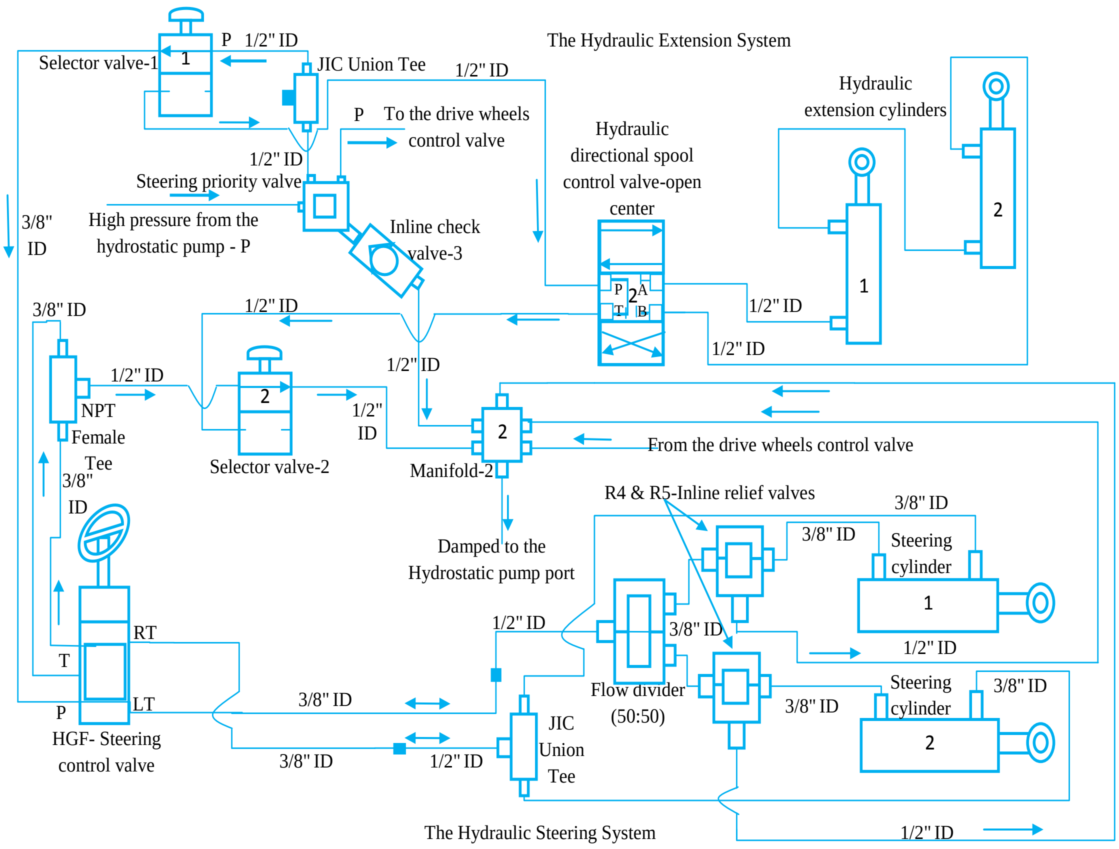

Figure A-3. The hydraulic system components of the harvesting tunnel width extension and the steering drive system of the preliminary shaker machine.

The Modified Hydraulic Control System of the Beaters Shaking Speed with a Shaker Brake System

The hydraulic brake circuit of the previous hydraulic shakers' motors (that have brake ports) has been excluded due to the new hydraulic motors of the shakers movement do not require brake ports.

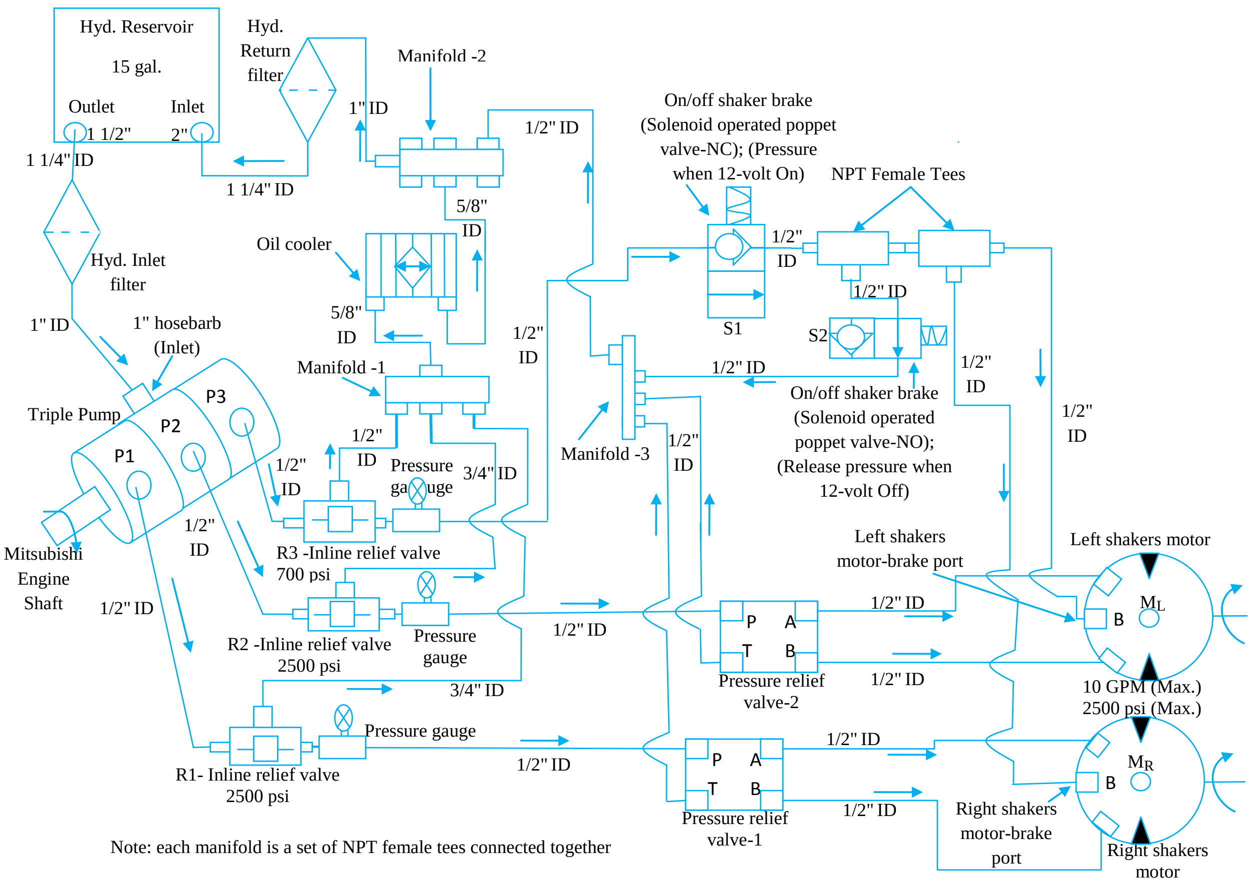

Figure A-4. Previous hydraulic system components of the two canopy shakers units with the eliminated shakers motors-brake ports (two on/off solenoid valves).

APPENDIX B
A PROTOTYPE OF THE SELF-PROPELLED CITRUS CANOPY SHAKING MACHINE

The Overall Appearance of the Preliminary Citrus Harvesting Machine Design

Figure B-1. The final view of the preliminary design of the continuous citrus canopy shaking machine. A) The machine front view, B) rear view of the machine, C) the machine right side view and D) left side view of the citrus harvester design. [Photos courtesy of Naji Al-Dosary]

The Overall Appearance of the Final Citrus Harvesting Machine Design

A B C D

Figure B-2. The final view of the final design of the continuous citrus canopy shaking machine. A) The machine right side view, B) left side view of the citrus harvester design, C) rear view of the machine, and D) the machine front view. [Photos courtesy of Naji Al-Dosary]

The New Citrus Harvesting Machine Transportation

Figure B-3. Easy machine transportation. [Photo courtesy of Naji Al-Dosary]

The Machine Orientation Control System

The Hydraulic Cylinders for the Machine Steering Control System

A

B

Figure B-4. Two hydraulic cylinders utilized for the machine orientation system mounted on the front wheels frame of the citrus canopy shaking machine. A) The front right wheel and B) the front left wheel. [Photos courtesy of Naji Al-Dosary]

The Hydraulic Steering Control Valve for the Machine Steering Control System

Figure B-5. A steering control valve with its steering wheel utilized for the machine orientation system placed on the front top of the citrus canopy shaking machine. [Photo courtesy of Naji Al-Dosary]

The Improvement of the Canopy Shaker Systems

Basic Components of the Initial and Final Shaker Systems

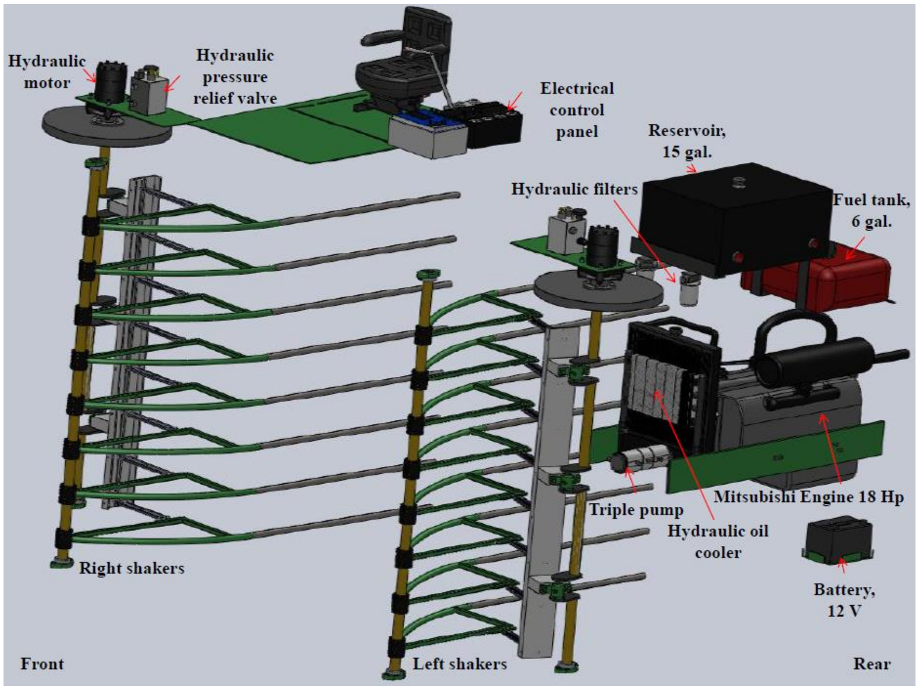

Figure B-6. Basic components of the preliminary canopy shaker units.

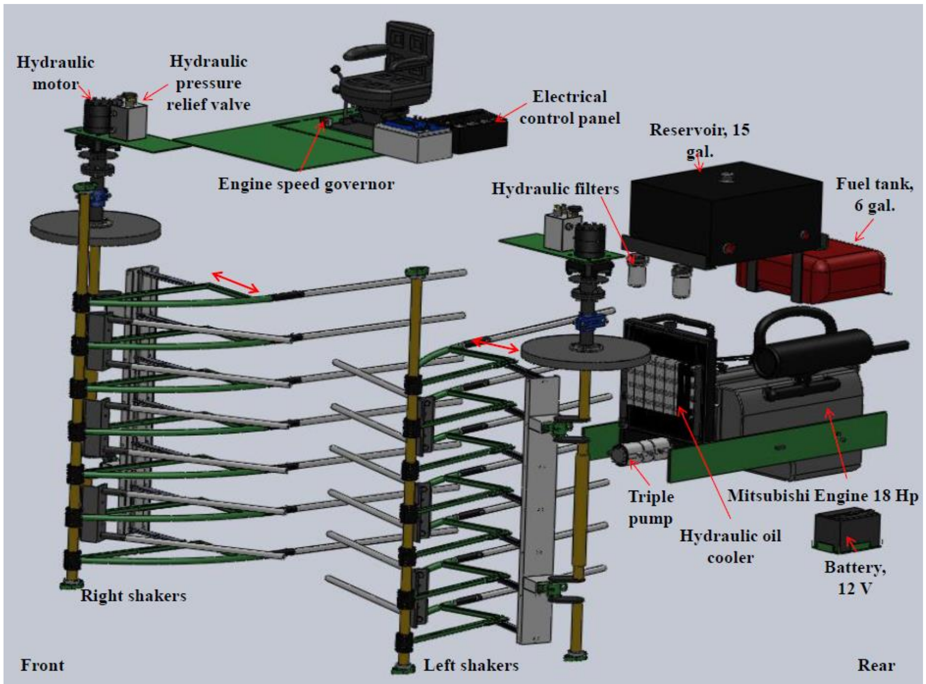

Figure B-7. Basic components of the final canopy shaker units.

APPENDIX C
THE ACCELERATION MAGNITUDE

Effect of the Shaking Beaters' Penetration of the Preliminary Citrus Harvesting Machine on the Acceleration Magnitude Distribution in the Grapefruit Tree Canopy

Table C-1. A precise average magnitude of the acceleration (g) among the tree canopy branches, depending on the delimited accelerometer sensors locations, and the machine operating variables into one tree canopy (the pre-test results).

No. of Accel. Sensor	Accelerometer Sensors Locations			Branch Dia. at the Posted Sensor (in)	First Trial (10 inches of turn buckle linkage)		Second Trial (11 inches of turn buckle linkage)		Third Trial (12 inches of turn buckle linkage)	
	Into the Tree Canopy	From Main Trunk (in)	From Ground (in)		Ave. of Max. Accel. Mag.(g)	Ave. of Gravi. Accel. (g)	Ave. of Max. Accel. Mag. (g)	Ave. of Gravi. Accel. (g)	Ave. of Max. Accel. Mag.(g)	Ave. of Gravi. Accel. (g)
1	Right edge	36	54	0.56	5.559	1.298	6.151	1.268	4.07	1.17
2	Right edge, Top	8	73	0.74	2.74	0.988	4.319	0.989	1.988	0.963
3	Right edge, Down	20	35	1.19	3.782	0.996	3.516	0.973	3.13	0.992
4	Left edge, Top	29	57	0.72	4.604	1.110	4.799	1.063	7.804	1.181
5	Back edge, Right	28	50	0.66	3.343	1.106	2.999	1.081	4.23	1.104
6	Central edge, Left, Back	15	58	1.25	1.884	1.045	1.691	1.03	2.588	1.044
7	Left edge, Front	31	52	0.82	4.427	1.155	3.763	1.113	5.041	1.154
8	Central edge, Top, Left, Front	8	72	0.55	1.91	1.034	2.228	1.029	2.561	1.033
9	Central edge, Left, Back	30	75	0.68	2.823	1.089	2.464	1.075	3.45	1.095
10	Right edge, Front, Down	31	38	0.90	6.074	1.181	7.255	1.301	6.457	1.274
11	Central edge, Front, Top	33	58	0.71	2.877	1.057	2.217	1.053	2.169	1.050
12	Left edge	33	40	0.63	4.07	1.236	3.348	1.163	6.207	1.264
13	Left edge, Top	15	58	0.69	2.361	1.027	2.677	1.021	3.292	1.052
14	Left edge, Front	24	36	0.85	2.622	1.068	2.592	1.063	2.738	1.075
15	Central edge, Back, Down, Rear of the main trunk	20	27	0.90	1.971	0.986	2.207	0.975	1.994	0.985
Ave. (g)					3.403^{b}	1.092	3.482^{ab}	1.08	3.848^{a}	1.096
S.D. (g)					1.772	0.100	1.717	0.096	1.879	0.096

Effect of the Beaters' Shaking Speeds of the Preliminary Citrus Harvesting Machine on the Acceleration Magnitude Distribution in the Grapefruit Trees Canopies

Table C-2. A precise average magnitude of the acceleration (g) among the tree canopy branches, depending on the delimited accelerometer sensors locations, and the machine operating variables at three different trees canopies (the pre-test results).

No. of Trees	No. of Accel. Sensors	Accelerometer Sensors Locations			Branch Dia. at the Posted Sensor (in)	First Trial (first beaters shaking speed)		Second Trial (second beaters shaking speed)	
		Into the Tree Canopy	From Main Trunk (in)	From Ground (in)		Ave. of Max. Accel. Mag. (g)	Ave. of Gravi. Accel. (g)	Ave. of Max. Accel. Mag. (g)	Ave. of Gravi. Accel. (g)
1	1	Left edge	18	37	1.28	2.674	1.066	4.28	1.16
	2	Left edge, Top	12	65	0.74	3.47	1.011	4.216	1.074
	3	Central edge, Back	21	27	0.91	2.088	0.935	1.933	0.955
	4	Right edge	24	34	1.41	7.387	1.242	7.52	1.529
	5	Right edge Top, Back	12	56	0.73	3.8	1.041	4.698	1.097
2	6	Left edge	32	45	1.00	3.188	1.176	4.884	1.317
	7	Left edge, Top	15	57	0.78	3.01	1.022	5.907	1.126
	8	Right edge, Top, Back	20	62	0.57	4.32	1.229	6.947	1.411
	9	Right edge, Down	13	31	0.83	3.995	1.113	5.74	1.212
	10	Right edge, Top, Front	17	52	0.58	2.66	1.036	4.759	1.086
3	11	Left edge	20	44	0.71	3.756	1.08	4.667	1.19
	12	Central edge, Right, Front	15	56	0.69	2.286	0.997	3.425	1.07
	13	Left edge, Back	24	40	0.87	2.409	1.037	4.024	1.194
	14	Right edge	16	40	0.71	6.168	1.176	8.004	1.3
	15	Central edge, Right, Top	8	64	0.89	3.54	1.055	4.652	1.143
Ave. (g)						3.65[a]	1.081	5.044[a]	1.191
S.D. (g)						1.708	0.091	1.883	0.156

APPENDIX D
THE SHAKING BEATERS POSITIONS

The New Shakers Penetrations into the Grapefruit Tree Canopy

For the final citrus harvester design, the shaking beaters are still dragged within the tree canopy, but the intimate engagement between the canopy and shaking beaters will be increased by increasing the lengths of the turnbuckles. The shaking beaters penetrations into the grapefruit canopy, depending on the turn buckle lengths, and also based on no load by the tree branches are shown in Table D-1. Moreover, the lowest shaking beaters height from the ground is 28 inches as well as the height of the top shaking beaters from the ground is 76 inches and 28 inches from top of internal tunnel of the machine (Figure D-1).

Table D-1. The shaking beaters penetrations into the grapefruit canopy depending on the turn buckle length.

		The Main Beaters		The Extra Beaters	
Crank Position (one full cycle)	The Beaters Penetration Based on the Turn Buckle Length (in)	Distance Between the Internal Body of the Harvester and a Free End of Beater (in)	Distance Between Free Ends of Two Beaters (in)	Distance Between the Internal Body of the Harvester and a Free End of Beater (in)	Distance Between Free Ends of Two Beaters (in)
Retraction Position	12	12	45	19.50	30
	15	20	29	23	23
	16	22	25	24.50	20
Extension Position	12	29	11	27	15
	15	36	Interaction as 3 inches	29	11
	16	37	Interaction as 5 inches	30	9

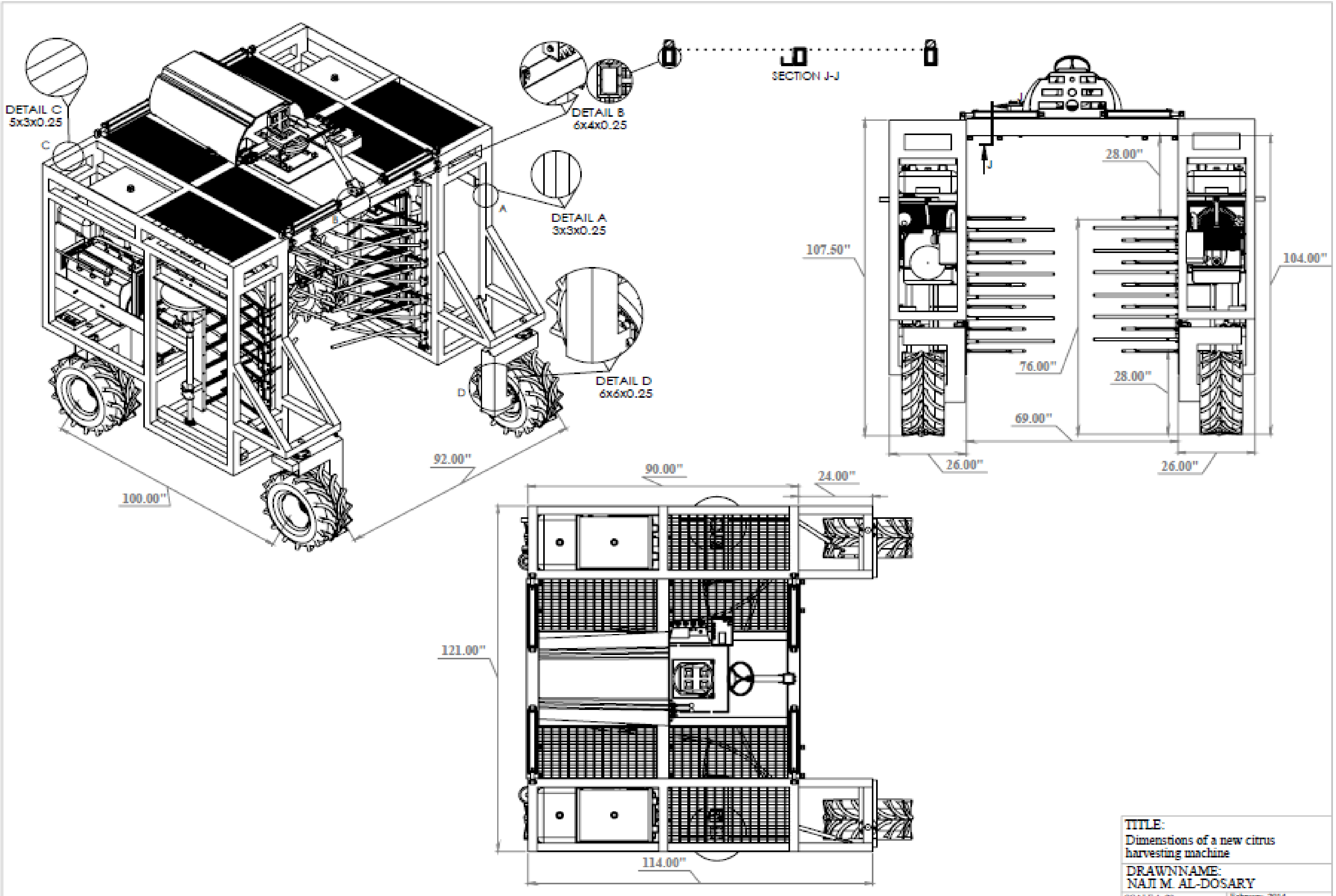

Figure D-1. Dimensions of the new self-propelled canopy shaker machine.

APPENDIX E
THE DEVELOPMENT TEAM

A New Citrus Harvesting Concept

This project was funded by GeoSpider, Inc. through a research award funded by the USDA NIFA SBIR program grant number 2011-33610-30458. The concepts developed were the results of GeoSpider, Inc Patent Pending established in 2004. Correspondingly, the basic elements of the citrus canopy harvester with the basic contributions of its design are presented in Table E-1.

Table E-1. Directory of the basic contribution of the citrus harvester elements design

Series	Citrus Harvesting Machine Structures	Design Perspectives	Technical Services
1	Harvesting Machine Frame Design	Naji Al-Dosary, Thomas Burks, and Mike Zingaro	Michael Zingaro
2	Two Shaking Units Design	Naji Al-Dosary, Thomas Burks, and Mike Zingaro	Naji Al-Dosary and Michael Zingaro
3	Harvester Wheel Frame Design	Michael Zingaro and Thomas Burks	Michael Zingaro
4	Principle of the Hydraulic System Design	Thomas Burks and Naji Al-Dosary	Thomas Burks, Naji Al-Dosary, and Michael Zingaro
5	Principle of the Electrical System Design	Thomas Burks and Naji Al-Dosary	Thomas Burks, Naji Al-Dosary, and Michael Zingaro
6	Funder and Purchase of Materials	GeoSpider, Inc.	Thomas Burks and Michael Zingaro
7	Machine Performance Tests	Naji Al-Dosary and Thomas Burks	Naji Al-Dosary and Michael Zingaro

In addition, the University of Florida development team, posing with their accomplished construction of the first prototype of the self-propelled citrus canopy shaking machine for Florida citrus trees harvesting (Figure E-1) are, from right to left, Dr. Thomas F. Burks, Naji M. Al-Dosary, and Michael J. Zingaro.

Considerately, the intellectual property contained within this dissertation is managed through the University of Florida's Office of Technology Licensing. Therefore any use of these concepts, without the express consent of the University of Florida, Dr. Thomas F. Burks, and Naji M. Al-Dosary are prohibited.

Figure E-1. The self-propelled canopy shakers machine development team. [Photo courtesy of Naji Al-Dosary, the end of year 2013]

APPENDIX F
PERFORMANCE OF THE NEW CITRUS CANOPY SHAKER

The Final Results of the New Citrus Harvesting Machine Performance

Practical experiments on the final prototype of the citrus harvester were carried out at the Plant Science Research and Education Center in Citra (PSREC) during the winter harvest of 2014. The results are shown in the following tables for the various test parameter combinations (Tables F-1, F-2, F-3, and F-4).

Table F-1. Amount of the detached grapefruit (fruits/tree).

	Detached Grapefruit (fruits/tree)			
Beaters Position (Turn Buckle Length) (inch)	Harvester Forward Speed (mi/hr)			
	Slow (0.62)		Fast (1.42)	
	Shakers Speed (inch/sec)		Shakers Speed (inch/sec)	
	Low (56.50)	High (73)	Low (56.50)	High (73)
Default (12, 14, and 15)	97	192	56	124
	68	163	86	122
	109	168	58	114
	130	141	81	129
	111	160	67	124
12	37	56	55	30
	75	55	57	34
	80	73	65	28
	72	78	74	47
	80	31	47	96
16	80	61	52	104
	101	103	83	111
	79	53	69	46
	70	88	91	84
	98	101	107	131

Table F-2. Amount of remaining grapefruit on trees (fruits/tree).

Beaters Position (Turn Buckle Length) (inch)	Remaining Fruit on the Tree (fruits/tree)			
	Harvester Forward Speed (mi/hr)			
	Slow (0.62)		Fast (1.42)	
	Shakers Speed (inch/sec)		Shakers Speed (inch/sec)	
	Low (56.50)	High (73)	Low (56.50)	High (73)
Default (12, 14, and 15)	20	14	21	42
	23	24	27	15
	20	30	52	33
	38	18	28	15
	43	7	45	37
12	12	11	39	50
	11	29	45	36
	42	31	39	42
	76	52	43	12
	35	41	30	40
16	4	0	13	14
	25	6	24	1
	11	6	24	4
	30	4	18	8
	11	14	18	4

Table F-3. Grapefruit detachment percentages (%).

Beaters Position (Turn Buckle Length) (inch)	Fruit Detachment Percentage (%) — Harvester Forward Speed (mi/hr): Slow (0.62) — Shakers Speed (inch/sec)		Fast (1.42) — Shakers Speed (inch/sec)	
	Low (56.50)	High (73)	Low (56.50)	High (73)
Default (12, 14, and 15)	82.91	93.20	72.73	74.70
	74.73	87.17	76.11	89.05
	84.50	84.85	52.73	77.55
	77.38	88.68	74.31	89.58
	72.08	95.81	59.82	77.02
12	75.51	83.58	58.51	37.50
	87.21	65.48	55.88	48.57
	65.57	70.19	62.50	40
	48.65	60	63.25	79.66
	69.57	43.06	61.04	70.59
16	95.24	100	80	88.14
	80.16	94.50	77.57	99.11
	87.78	89.83	74.19	92
	70	95.65	83.49	91.30
	89.91	87.83	85.60	97.04

Table F-4. Averages of the grapefruit detachment percentage (%).

Beaters Position (Turn Buckle Length) (inch)	Fruit Detachment Percentage (%)			
	Harvester Forward Speed (mi/hr)			
	Slow (0.62)		Fast (1.42)	
	Shakers Speed (inch/sec)		Shakers Speed (inch/sec)	
	Low (56.50)	High (73)	Low (56.50)	High (73)
12	69.30	64.46	60.24	55.26
Default (12, 14, and 15)	78.32	89.94	67.14	81.58
16	84.62	93.56	80.17	93.52

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BIOGRAPHICAL SKETCH

In 1970, Naji Al-Dosary was born in the City of Al-Badi, south of the Al-Aflaj Province. He received his Bachelor of Agricultural Engineering in 1993 from the College of Food and Agricultural Sciences at the King Saud University, Riyadh. Since then, he began working with the Ministry of Agriculture at Al-Aflaj Bureau of the Ministry of Agriculture in Al-Aflaj Province, Riyadh. In 2000, Naji got married to Ietemad. They have three daughters, Sarah, Shekah, and Asla and one son, Mordi. In 2005, he got his Master of Science in the agricultural engineering program with a major in farm power and machinery from the College of Food and Agricultural Sciences at the King Saud University at City of Riyadh, capital of Saudi Arabia. In 2011, he received his second Master of Engineering with a major in the machine systems development program from the Agricultural and Biological Engineering Department at the University of Florida in Gainesville, State of Florida. Naji Al-Dosary has continued to pursue his graduate education for getting a doctorate of philosophy in agricultural and biological engineering with a major in the machine systems development from the Agricultural and Biological Engineering Department, Engineering College at the University of Florida since 2007. Accordingly, he received his Doctor of Philosophy from the University of Florida in the spring of 2014.