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PREDICTION OF THE SUITABLE AMPLITUDE OF SHAKING UNIT FOR FRUIT HARVESTING

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ABSTRACT

A mathematical analysis is provided for predicting the suitable-shaking amplitude of limb tree shaker. The derived equation correlates the pulling force to fruit mass ratio, stem length, shaking frequency and damping ratio with the shaking amplitude. The mathematical equation was experimentally checked for two citrus varieties; Valencia and Grapefruit.

The practical study showed that, the derived equation could be used with enough confidence in predicting the shaking amplitude of shaking unit in mechanical harvesting of citrus fruits. The optimum fruit removal percentages without limb damage was about 97 % for both varieties. These values were obtained at 0.4- 1.2 cm amplitude and 7- 6 Hz shaking frequency.

***Keywords*: Citrus, Mechanical harvesting, Mathematical analysis, Shaking, Amplitude.**

INTRODUCTION

The use of mechanical harvesting by shaking or vibration action has been the most common mechanical approach to fruit detachment. The most successful approach for tree fruits has been to attach a mechanical shaking device to the tree limbs or tree trunk. Tree shakers are used extensively on some crops such as peaches, nuts, red tart cherries, olives, mango, citrus and plums.

Coppock and Hedden 1968 and Tsatsarelis et al. 1980 mentioned that the factors affecting the mechanical harvesting by shaking is classified into two groups; machine factors (frequency, amplitude and direction of shaking) and fruit & stem factors (Fruit variety, fruit volume, fruit maturity, fruit mass, pull force to fruit mass ratio, stem length, stem diameter and stem stiffness). ***Brown 2002*** designed a Stackhouse shaker heads for citrus harvesting, and used an extended clamp area that enabled the shaker to be placed on the major scaffold limbs when necessary. Fruit removal ranged from 90 to 95%. The shaker can be mechanically timed to produce circular, star-shaped, or straight-line amplitude patterns. The straight-line amplitude is perpendicular

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to the shaker clamp pads, gives excellent and quick fruit removal, and has less occurrence of bark injury when the cambium is active.

Ghonimy 2002 found that the optimum fruit removal percentage of mango without limb breakage can be realized when shaking is applied at 25 to 30 mm amplitude, 15 to 20 Hz frequency and 5 to 10 sec shaking time. For these conditions fruit removal percentage was 86.0 to 98.4 %. He also reported that the fruit removal percentage (*FR*) and both frequency *(f)* and amplitude (*A)* could be correlated as in the following equation:

$$FR = 100 \cdot \left(1 - e^{-1.19x10^{-3} \cdot f^{2.0} \cdot A^{0.62}}\right)$$

Abou El magd et al. 2002 designed and developed a cone-end detached for orange picking. The design was based on deducing relevant parameters from theory to represent torsion forces necessary for fruit detachment and the physical properties of both fruit and twigs. Three operating parameters namely: the friction coefficient between the cone and fruit surface, the cone rotating speed and the cone apex angle were considered for the technical evaluation of the developed prototype. They also found that the minimum fruit detachment time was obtained at a friction coefficient of about 0.81 for Washingtonia variety. The cone rotating speed of 680 rpm gave the best results for the shortest remaining twig height of 0.88 mm and the optimum cone angle of 52^o. ***Whitney et al. 2001*** compared the multidirectional and linear shaking patterns to remove orange from trees to measure the fruit removal performance. They concluded that the linear shaking pattern removed 1 to 6 percentage points more oranges than did the multidirectional shaking pattern with a 6 to 7cm displacement at 7 Hz frequency and a shaking time of 5 to 10 sec/tree. ***Peterson and Wolford 2001*** developed a mechanical harvester to harvest sweet cherries for the fresh market. The harvester operator used joysticks to position and engaged a rapid displacement actuator on main scaffolds to affect fruit removal. The three main scaffolds per tree were inclined to reduce damage as cherries fell to the catching surface. Ethrel was used to reduce the fruit retention force of mature cherries to enable removal without branch damage. A catching conveyor was designed to intercept falling fruit without damage and elevate the fruit to a collecting conveyor. Mechanically harvested cherries had only 2-6% more damage than did commercially hand-harvested cherries and graded 85-92% marketable. ***Horvath and Sitkei 2005*** used a direct energy method to measure the effective damping coefficient of the root-soil body and of primary limbs of plum trees. Measurements have shown that the vibrating soil-mass has a large damping capacity. Measurements were carried out in a 12-year-old plum orchard. Trunk diameters varied between 130 and 250 mm, the respective canopy radius varied between 2.2 and 3.0 m,

and each tree had five to seven primary limbs. The total damping loss originated mainly from the vibrating soil-mass and tree canopy.
This current work aimed to mathematically correlate the main factors affecting the mechanical harvesting by shaking in order to predict the suitable amplitude of shaking unit to remove the fruit from the stem.

MATERIALS AND METHODS

A scientific approach based mainly on the mathematical analysis was followed in this study. The factors affecting the mechanical harvesting by shaking were first determined. These affecting factors were then related to the shaking amplitude in a mathematical relationship.

1. Mathematical analysis approach

In fruit mechanical harvesting by shaking, the external vibrating energy is given to the tree branch or tree limb for fruit removing. This energy is converted to different energy forms. In this research, La Grange equation, eq. (1), ***(Thomson, 1972)*** was used as the most suitable mathematical analysis approach.

$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \theta^{\bullet}}\right)-\frac{\partial KE}{\partial \theta}+\frac{\partial PE}{\partial \theta}+\frac{\partial D}{\partial \theta^{\bullet}}=\frac{\partial W}{\partial \theta} \qquad (1)$$

Where:

KE = Kinetic energy, N.m;
$\theta^{\bullet}$ = Fruit-stem angular velocity, rad/s
θ = Angular displacement of the fruit-stem from vertical position i.e, the natural balanced position, rad;
PE = Potential energy, N.m;
D = Infinitesimal dissipated energy per unit time, N.m/s;
W = External work, N.m.

La Grange equation is considered as energy balance equation for any vibrating system. In this equation, the external work was expressed as a function of different converted energy forms, i.e, kinetic energy consumed in fruit moving, potential energy consumed in changing fruit position and the internal & external dissipated energy.

The partial differential equation is to be solved by a suitable complex method to mathematically expressing the effect of different affecting factors on the shaking amplitude, which causes fruit separation. By using this complex method, the above partial differential equation was converted to ordinary differential equation.

2. General assumptions and simplifications for the mathematical manipulation

Some assumptions and simplifications were made in order to facilitate the mathematical manipulation as follows:

- The fruits are considered homogeneous with a constant density.
- The direction of shaking is considered horizontal.

3. Mathematical analysis for predicting the shaking amplitude

a. Kinetic energy (*KE*) consumed in fruit moving

The kinetic energy *(KE)* consumed in fruit moving depends upon the fruit mass *(m)* and fruit speed *(v)* as follow:

$$KE = \frac{1}{2} m v^2 \qquad (2)$$

From **Fig. (1)**, the fruit speed could be determined as follow

$$v^2 = \left(\ell \frac{d\theta}{dt} \cos\theta + \frac{dx}{dt} \right)^2 + \left(\ell \sin\theta \frac{d\theta}{dt} \right)^2 \qquad (3)$$

Where:

ℓ = Stem length, m;

x = Shaking displacement of limb, m;

θ = Angular displacement from vertical position, rad.

Substituting from equation (3) into equation (2) gives:

$$KE = \frac{m}{2} \left[\left(\frac{dx}{dt} \right)^2 + 2\ell \cdot \cos\theta \cdot \frac{dx}{dt} \cdot \frac{d\theta}{dt} + \ell^2 \left(\frac{d\theta}{dt} \right)^2 \right] \qquad (4)$$

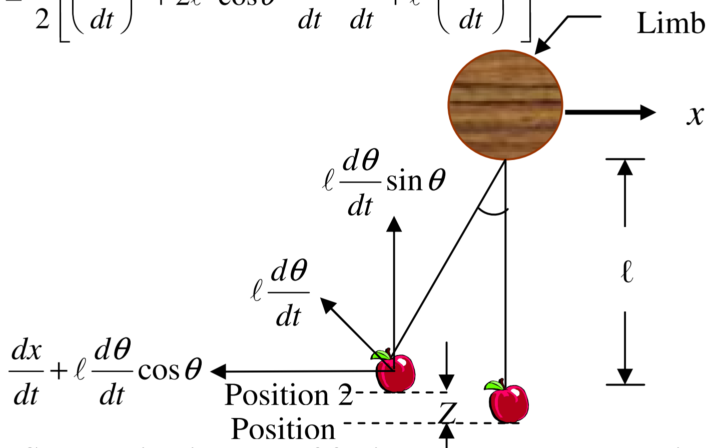


Fig. (1): Schematic diagram of fruit-stem movement during shaking

b. Potential energy (*PE*) consumed in changing fruit position

The potential energy *(PE)* consumed in changing fruit position depends upon, the fruit mass *(m)* and the vertical distance *(z)* between the primary and final position as follow;

$$PE = mgz \tag{5}$$

From fig. (1), $z = \ell - \ell \cos\theta$

$$\therefore PE = mg\ell(1-\cos\theta) \tag{6}$$

c. The infinitesimal dissipated energy per unit time (*D*)

The infinitesimal dissipated energy per unit time was used from equation (7) according to ***Harris 1996***

$$D = \frac{1}{2} C \theta^{\bullet 2} \tag{7}$$

Where:

C = Damping coefficient, N.m.sec;

$\theta^{\bullet}$ = Angular velocity, rad/s.

d. The external work (*W*)

The external work from shaking unit depends upon the limb mass with fruits and shaking displacement of limb as follow;

$$W = M * g * x \tag{8}$$

Where:

M = Limb mass with fruits, kg;

x = Shaking displacement of limb, m.

The left side of equation (1) was divided into four terms; $\frac{d}{dt}\left(\frac{\partial KE}{\partial \theta^{\bullet}}\right)$, $\frac{\partial KE}{\partial \theta}$, $\frac{\partial PE}{\partial \theta}$ and $\frac{\partial D}{\partial \theta^{\bullet}}$

- The first term:

Substituting from equation (4) into the first term gives

$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \theta^{\bullet}}\right) = \frac{d}{dt}\left\{\frac{\partial}{\partial \theta^{\bullet}}\left[\frac{m}{2}\left\langle\left(\frac{dx}{dt}\right)^2 + 2\ell\cos\theta\frac{dx}{dt}\cdot\frac{d\theta}{dt} + \ell^2\left(\frac{d\theta}{dt}\right)^2\right\rangle\right]\right\}$$

From the differentiation of the *KE* for $\theta^{\bullet}$ and time, it can lead to

$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \theta^{\bullet}}\right) = m\ell\left(\frac{d^2x}{dt^2}\cdot\cos\theta - \frac{dx}{dt}\cdot\frac{d\theta}{dt}\cdot\sin\theta + \ell\frac{d^2\theta}{dt^2}\right) \tag{9}$$

- The second term (useful energy):

Substituting from equation (4) into the second term gives:

$$\left(\frac{\partial KE}{\partial \theta}\right)=\frac{\partial}{\partial \theta}\left[\frac{m}{2}\left\langle\left(\frac{dx}{dt}\right)^2+2\ell\cos\theta\frac{dx}{dt}\cdot\frac{d\theta}{dt}+\ell^2\left(\frac{d\theta}{dt}\right)^2\right\rangle\right]$$

$$=-m\ell\frac{dx}{dt}\cdot\frac{d\theta}{dt}\cdot\sin\theta \qquad (10)$$

- The third term:

Substituting from equation (6) into the third term gives:

$$\frac{\partial PE}{\partial \theta}=\frac{\partial}{\partial \theta}\left[mg\ell(1-\cos\theta)\right] \quad = mg\ell\sin\theta \qquad (11)$$

- The fourth term:

Substituting from equation (7) into the fourth term gives:

$$\frac{\partial D}{\partial \theta^{\bullet}}=\frac{\partial}{\partial \theta^{\bullet}}\left[\frac{1}{2}C\left(\frac{d\theta}{dt}\right)^2\right]=C\frac{d\theta}{dt} \qquad (12)$$

Substituting from equation (8) into the right side of equation (1) gives:

$$\frac{\partial W}{\partial \theta}=\frac{\partial}{\partial \theta}(M*g*x)=0 \qquad (13)$$

Because the external work (*W*) is independent of (*θ*).

Substituting from equations (9), (10), (11), (12) and (13) into equation (1) and dividing it by $m\ell$ gives:

$$\frac{d^2x}{dt^2}\cos\theta+\frac{d^2\theta}{dt^2}\ell+g\sin\theta+\frac{d\theta}{dt}\cdot\frac{C}{m\ell}=0 \qquad (14)$$

Equation (14) is second order differential equation

For small θ values: $\cos\theta=1, \quad \sin\theta=\theta$

Substituting these values into eq. (14) and dividing it by ℓ gives:

$$\frac{1}{\ell}\cdot\frac{d^2x}{dt^2}+\frac{d^2\theta}{dt^2}+\frac{g}{\ell}\cdot\theta+\frac{C}{m\ell^2}\cdot\frac{d\theta}{dt}=0 \qquad (15)$$

$$\because \frac{C}{m\ell^2}=2\zeta\cdot\sqrt{g/\ell} \quad \text{according to } \textbf{\textit{Thomson, 1972}} \qquad (16)$$

Where:

C = Damping coefficient, N.m.sec;
m = Fruit mass, kg;
ℓ = Stem length, m;
ζ = Damping ratio, dimensionless.

Substituting from equation (16) into equation (15) gives:

$$\therefore \frac{1}{\ell}\cdot\frac{d^2x}{dt^2}+\frac{d^2\theta}{dt^2}+\frac{g}{\ell}\cdot\theta+2\zeta\cdot\sqrt{g/\ell}\cdot\frac{d\theta}{dt}=0 \quad (15\text{-a})$$

Equation (15- a) was solved by complex method as follows.

Since, $x=\chi\cdot e^{i\omega t}$, $\frac{dx}{dt}=i\cdot\omega\cdot\chi\cdot e^{i\omega t}$, $\frac{d^2x}{dt^2}=-\omega^2\cdot\chi\cdot e^{i\omega t}$

$\theta=\vartheta\cdot e^{i(\omega t+\phi)}$, $\frac{d\theta}{dt}=i\cdot\omega\cdot\vartheta\cdot e^{i(\omega t+\phi)}$, $\frac{d^2\theta}{dt^2}=-\omega^2\cdot\vartheta\cdot e^{i(\omega t+\phi)}$

Where:

χ = Linear motion amplitude

ϑ = Angular motion amplitude

ϕ = Phase shift

ω = Shaking frequency

Substituting the values of $\frac{d^2x}{dt^2},\frac{d^2\theta}{dt^2},\frac{d\theta}{dt}$ & θ into equation (15-a) and dividing the product by $e^{i\omega t}$ gives:

$$-\omega^2\cdot e^{i\phi}+2i\omega\zeta\cdot\sqrt{g/\ell}\cdot e^{i\phi}+\frac{g}{\ell}\cdot e^{i\phi}=\frac{\omega^2\chi}{\ell\cdot\vartheta} \quad (17)$$

$$\because e^{i\phi}=\cos\phi+i\cdot\sin\phi \quad (\textbf{\textit{Thomson, 1972}})$$

$$-\omega^2(\cos\phi+i\cdot\sin\phi)+2i\omega\zeta\sqrt{g/\ell}\cdot(\cos\phi+i\cdot\sin\phi)+\frac{g}{\ell}\cdot(\cos\phi+i\cdot\sin\phi)=\frac{\omega^2\chi}{\ell\cdot\vartheta} \quad (18)$$

Equation (18) includes two parts, real and imaginary parts:

The real part:

$$-\omega^2\cos\phi-2\omega\sqrt{\frac{g}{\ell}}\zeta\sin\phi+\frac{g}{\ell}\cos\phi=\frac{\omega^2\chi}{\ell\cdot\vartheta}$$

$$\left(-\omega^2+\frac{g}{\ell}\right)\cos\phi-2\omega\sqrt{\frac{g}{\ell}}\zeta\sin\phi=\frac{\omega^2\chi}{\ell\cdot\vartheta} \quad (19)$$

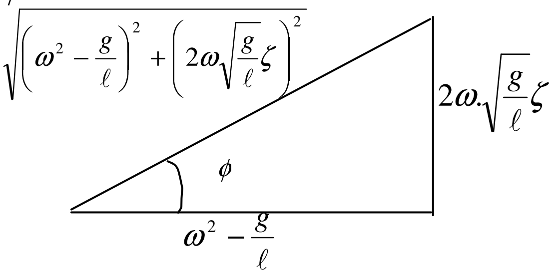
The imaginary part:

$$-\omega^2 i\sin\phi+2i\omega\zeta\cdot\sqrt{g/\ell}\cdot\cos\phi+\frac{g}{\ell}i\sin\phi=0$$

Dividing by ***i*** gives:

$$2\omega\zeta\cdot\sqrt{g/\ell}\cdot\cos\phi=\omega^2\sin\phi-\frac{g}{\ell}\sin\phi$$

From the attached figure,



$$\sin\phi=\frac{2\omega.\sqrt{\frac{g}{\ell}}\cdot\zeta}{\sqrt{\left(\omega^2-\frac{g}{\ell}\right)^2+\left(2\omega\sqrt{\frac{g}{\ell}}\cdot\zeta\right)^2}} \quad (20),\qquad \cos\phi=\frac{\omega^2-\frac{g}{\ell}}{\sqrt{\left(\omega^2-\frac{g}{\ell}\right)^2+\left(2\omega.\sqrt{\frac{g}{\ell}}\cdot\zeta\right)^2}} \quad (21)$$

From the real part:
Substituting from equations (20) and (21) into equation (19) gives:

$$-\frac{\left(\omega^2-\frac{g}{\ell}\right)\cdot\left(\omega^2-\frac{g}{\ell}\right)}{\sqrt{\left(\omega^2-\frac{g}{\ell}\right)^2+\left(2\omega\sqrt{\frac{g}{\ell}}\cdot\zeta\right)^2}}-\frac{\left(2\omega\sqrt{\frac{g}{\ell}}\cdot\zeta\right)^2}{\sqrt{\left(\omega^2-\frac{g}{\ell}\right)^2+\left(2\omega\sqrt{\frac{g}{\ell}}\cdot\zeta\right)^2}}=\frac{\omega^2\chi}{\ell\vartheta}$$

$$\frac{-\left[\left(\omega^2-\frac{g}{\ell}\right)^2+\left(2\omega\sqrt{\frac{g}{\ell}}\cdot\zeta\right)^2\right]}{\sqrt{\left(\omega^2-\frac{g}{\ell}\right)^2+\left(2\omega\sqrt{\frac{g}{\ell}}\cdot\zeta\right)^2}}=\frac{\omega^2\chi}{\ell\vartheta}$$

$$\therefore\quad -\sqrt{\left(\omega^2-\frac{g}{\ell}\right)^2+\left(2\omega\sqrt{\frac{g}{\ell}}\cdot\zeta\right)^2}=\frac{\omega^2\chi}{\ell\vartheta} \qquad (22)$$

Thus, the amplitude of angular motion (ϑ) is:

$$\therefore \quad \vartheta = -\frac{\omega^2 \chi}{\ell * \sqrt{\left(\omega^2 - \frac{g}{\ell}\right)^2 + \left(2\omega\sqrt{\frac{g}{\ell}} \cdot \zeta\right)^2}} \tag{23}$$

Multiplying the two sides of equation (23) by ω

Thus,
$$|\omega\vartheta| = \frac{\omega^3 \chi}{\ell * \sqrt{\left(\omega^2 - \frac{g}{\ell}\right)^2 + \left(2\omega\sqrt{\frac{g}{\ell}} \cdot \zeta\right)^2}} \tag{24}$$

Since, the required inertia force for removing each fruit is equal to, $\text{mass} \times \text{acceleration}$. Thus,

$$F = (\omega\vartheta)^2 \ell \cdot m \tag{25}$$

Where:

F	=Detachment force, N;
m	= Fruit mass, kg;
ℓ	= Stem length, m;
$(\omega * \vartheta)$	= Maximum shaking frequency, rad/s.

Substituting from equation (24) into equation (25), gives:

$$F = \frac{\omega^6 \chi^2 m}{\ell\left[\left(\omega^2 - \frac{g}{\ell}\right)^2 + \left(2\omega\sqrt{\frac{g}{\ell}} \cdot \zeta\right)^2\right]}$$

Thus, solving for χ gives:

$$\chi = \frac{\left(\frac{F}{m}\ell \cdot \left[\left(\omega^2 - \frac{g}{\ell}\right)^2 + \left(2\omega\sqrt{\frac{g}{\ell}} \cdot \zeta\right)^2\right]\right)^{1/2}}{\omega^3} \tag{26}$$

Where:

χ	= Shaking amplitude, m;
F	= Detachment force, N;
m	= Fruit mass, kg;
ℓ	= Stem length, m;
ω	= Shaking frequency, rad/s;
ζ	= Damping ratio, dimensionless.

Laboratory and field experiments

Laboratory tests included some physical properties of citrus fruit (attachment force, weight, volume& density) and dimensional characteristics of stem (length& diameter). Field experiments were carried out at the Experimental Station Farm, Faculty of Agriculture, Cairo University. During field experiments, the limbs of citrus were shaked by a tree shaking machine **Fig. 2**, which was developed by ***Ghonimy 2002*.** This machine was operated using a tractor (KUBOTA model L 245), 25 hp at 2800 rpm, 3 point hitch category I and lift capacity was 500 kg. Nylon nets were fixed on stands for receiving the removed fruits. The maximum adjustable height of the stands was 1.5m from the ground surface.

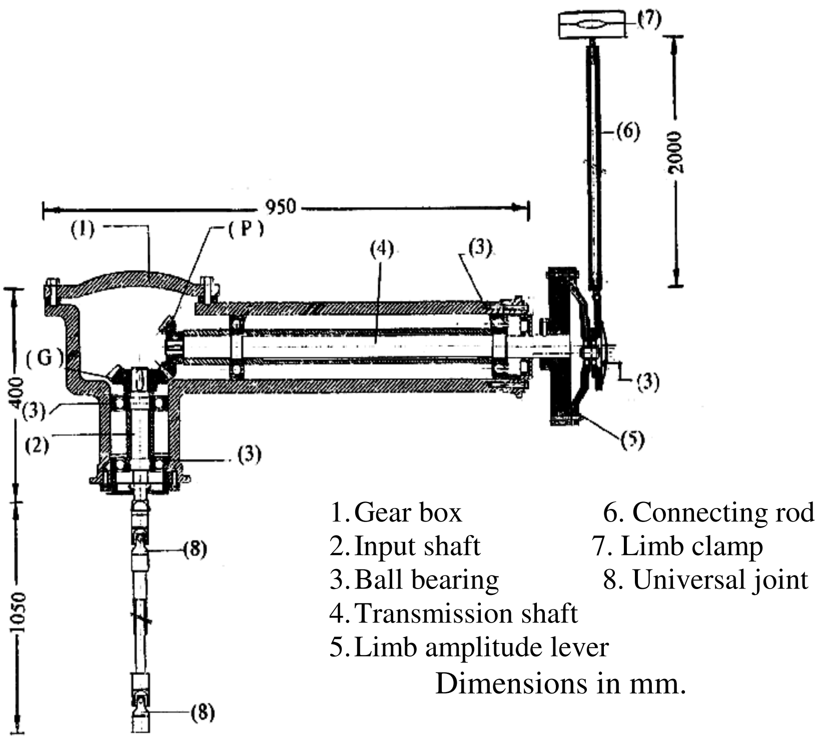


Fig. (2): Sectional plan of the used tree shaking machine

Treatments

1. Amplitude (χ)

The tested values of amplitude were taken from equation (26). The tested values of amplitude were (6.2, 2.6, 1.2 & 0.5 cm) and (4.4, 1.9, 0.9 & 0.4 cm) for Valencia and Grapefruit varieties respectively.

2. Frequency (*ω*)

The tested values of frequency (*ω*) were taken according to ***O'brien et al. 1986.*** The tested values of frequency were 4, 5, 6 and 7 Hz at 10 sec shaking time.

Measurements and calculations

1. Length and diameter of stem

The length and diameter of the stem were determined by using vernier caliper (accuracy = ± 0.1 mm).

2. Detachment force (*F*)

The detachment force of fruit (*F*) was determined by using digital force gauge (accuracy = ± 0.01 N).

3. Frequency (*ω*)

The frequency was determined by using digital tachometer.

4. Limb damage at the point of contact with clamp of shaking machine

The damage of tree limb at the point of contact with the clamp of tree shaking machine was determined in terms of bruise volume of limb damage.

5. Breakage of shaked limb

The breakage of shaked limb was measured in terms of length of breakage zone by using vernier caliper.

6. Fruit removal percentage (*FRP*)

$$FRP = \frac{N_1}{N_2} \times 100 \qquad (27)$$

Where:

FRP = Fruit removal percentage, %;

N_1 = Number of harvested citrus fruits from the limb

N_2 = The total number of citrus fruits on the limb.

7. Damping ratio (ζ)

The damping ratio was calculated from eq. (28) according to ***Thomson 1972.***

$$\zeta = \sqrt{1 - \frac{\omega_d^{\,2} * \ell}{g}} \qquad (28)$$

Where:

ω_d = Damping frequency $= 2\pi/t$, rad/s;

t = Time of one cycle, sec.

A test was run to measure the time of one cycle (t). The citrus-stem system was fixed vertically on the plate by a support. The fruit was moved horizontally. The time spent of one cycle was determined using stopwatch.

RESULTS AND DISCUSSION

1. Laboratory tests

The average values of fruit detachment force (*F*), fruit mass (*m*), stem length (*ℓ*), stem diameter (*d*) for two citrus varieties (Valencia and Grapefruit) at different ripening stages are shown in table (1).

From table (1), it is clear that the detachment force of Valencia and Grapefruit varieties decreased with increasing the maturity. For Valencia (**Va**) variety, a reduction of 22.7 to 27.2 % in the detachment force was observed with the increasing of maturity. For Grapefruit variety (**Gr**), a reduction of 40.6 to 52.1 % in the detachment force was observed with the increasing of maturity. The fruit mass increased with increasing the maturity. An increase of (11.7 to 13.7 %) and (9.5 to 10 %) in the fruit mass were observed with the increasing of maturity in Valencia and Grapefruit respectively. Also, the ratio between the detachment force and fruit mass (*F*/*m*) decreased with increasing the maturity. Meanwhile, the values of changing rate of stem length and diameter were very small.

Table (1): Some properties of Valencia (Va) and Grapefruit (Gr) varieties and dimensional characteristics of stem at different ripening stages.

Variety	Repining stage		Fruit			Stem	
			F, N	***m***, kg	***F/m***, m/s^2	***ℓ***, mm	***d***, mm
Valencia	**Unripe**	**Average**	13.40	0.145	92.4	25.3	3.6
		STDEV	4.53	6.45	8.65	1.26	2.16
	Ripe	**Average**	10.36	0.165	62.8	25.4	3.7
		STDEV	3.64	8.16	9.31	0.94	1.65
	Overripe	**Average**	9.75	0.162	60.2	25.4	3.7
		STDEV	0.95	3.65	3.84	0.85	1.98
Grapefruit	**Unripe**	**Average**	9.72	0.210	46.3	27.1	3.2
		STDEV	5.12	8.95	6.65	1.64	3.45
	Ripe	**Average**	5.77	0.230	25.1	27.1	3.2
		STDEV	2.11	4.65	5.34	0.98	2.54
	Overripe	**Average**	4.66	0.231	20.2	27.1	3.2
		STDEV	0.86	6.84	2.05	1.87	3.65

F = Detachment force *m* = Fruit mass

ℓ = Stem length *d* = Stem diameter

2. Determination of the values of damping ratio (ζ)

Referring to the data in table (1) and equation (28), the values of damping ratio (ζ) are estimated and tabulated in table (2). It is clear that the average values of damping ratio (ζ) at any ripening stage are 0.106 and 0.132 for Valencia and Grapefruit respectively.

Table (2): The values of damping ratio (ζ)

Characteristics	Unripe		Ripe		Overripe	
	Va	Gr	Va	Gr	Va	Gr
ζ (Dimensionless)	0.111	0.132	0.106	0.132	0.106	0.132

3. Determination of the suitable values of shaking amplitude (χ)

To predict the suitable shaking amplitude of tree shaker, equation (26) was used. Using the laboratory measured values in table (1), the values of shaking frequency (4, 5, 6 and 7 Hz according to ***O'brien et al. 1986***) and the values of damping ratio from table (2) into equation (26) gave the suitable values of shaking amplitude table (3).

Table (3): The values of shaking amplitude (χ), cm.

Shaking frequency,		Unripe		Ripe		Overripe	
Hz	rad/s	Va	Gr	Va	Gr	Va	Gr
4	25.12	7.7	6.0	6.2	4.4	6.1	3.9
5	31.40	3.3	2.6	2.6	1.9	2.6	1.7
6	37.68	1.5	1.2	1.2	0.9	1.1	0.8
7	43.96	0.7	0.6	0.5	0.4	0.5	0.3

From table (3) it's clear that the maximum values of shaking amplitude was found at 4 Hz of shaking frequency, while the minimum values was found at 7 Hz of shaking frequency. Thus, there is an inverse proportionality between shaking frequency and shaking amplitude

4. Field experiments

To remove the ripe fruits only from the tree, shaking machine was tested in the field under four levels of shaking frequency and the corresponding levels of amplitude for ripe fruits at 10 sec shaking time. These levels are shown in table (4).

Table (4): The tested levels of frequency and amplitude

Shaking frequency, Hz	Amplitude, cm.	
	Va	Gr
4	6.2	4.4
5	2.6	1.9
6	1.2	0.9
7	0.5	0.4

4.1. Effect of frequency and amplitude on the fruit removal

The average values of fruit removal (***FRP***) at different values of shaking frequency and amplitude are shown in **Fig. (3)**.

From fig. 3-A, for Valencia variety, the fruit removal percentage are 86.4, 88.2, 89.6 and 90.3 % at frequencies and amplitudes (4 Hz and 6.2 cm), (5 Hz and 2.6 cm), (6 Hz and 1.2 cm) and (7 Hz and 0.5 cm) respectively. The fruit removal percentage increased by small percentage 1.8, 3.2 and 3.9 % when the frequency increased from 4 Hz to 5, 6 and 7 Hz respectively while the amplitude decreased from 6.2 cm to 2.6, 1.2 and 0.5 cm respectively.

From fig. 3-B, for Grapefruit variety, the fruit removal percentage are 88,91, 91 and 93.4 % at frequencies and amplitudes (4 Hz and 4.4 cm), (5 Hz and 1.9 cm), (6 Hz and 0.9 cm) and (7 Hz and 0.4 cm) respectively. The fruit removal percentage increased by small percentage 3, 3 and 5.4 % when the frequency increased from 4 Hz to 5, 6 and 7 Hz respectively while the amplitude decreased from 4.4 cm to 1.9, 0.9 and 0.4 cm respectively.

From the above results, it can be concluded that the suitable operating shaking frequency could be ranged between 4 Hz to 7 Hz. Also, the suitable operating shaking amplitude could be ranged between 6.2 cm to 0.5 cm for Valencia variety and from 4.4 cm to 0.4 cm for Grapefruit variety to keep the fruit removal percentage at suitable value.

4.2. The effect of frequency and amplitude on the limb damage

Personal meeting with experts in the field of horticulture, gave some conclusion concerning the damage and its harmful effects. If the depth of bruise through the affected limb does not penetrate inside the limb and does not reach the vascular bundles, it is considered safe enough to cause direct or indirect effect on the tree or on the yield. In quantitative expression, the damage is safe when its volume does not exceed 3.6 $cm^{3.}$ This value was calculated by multiplying the thickness of preiderm and cortex by the contact area of the clamp.

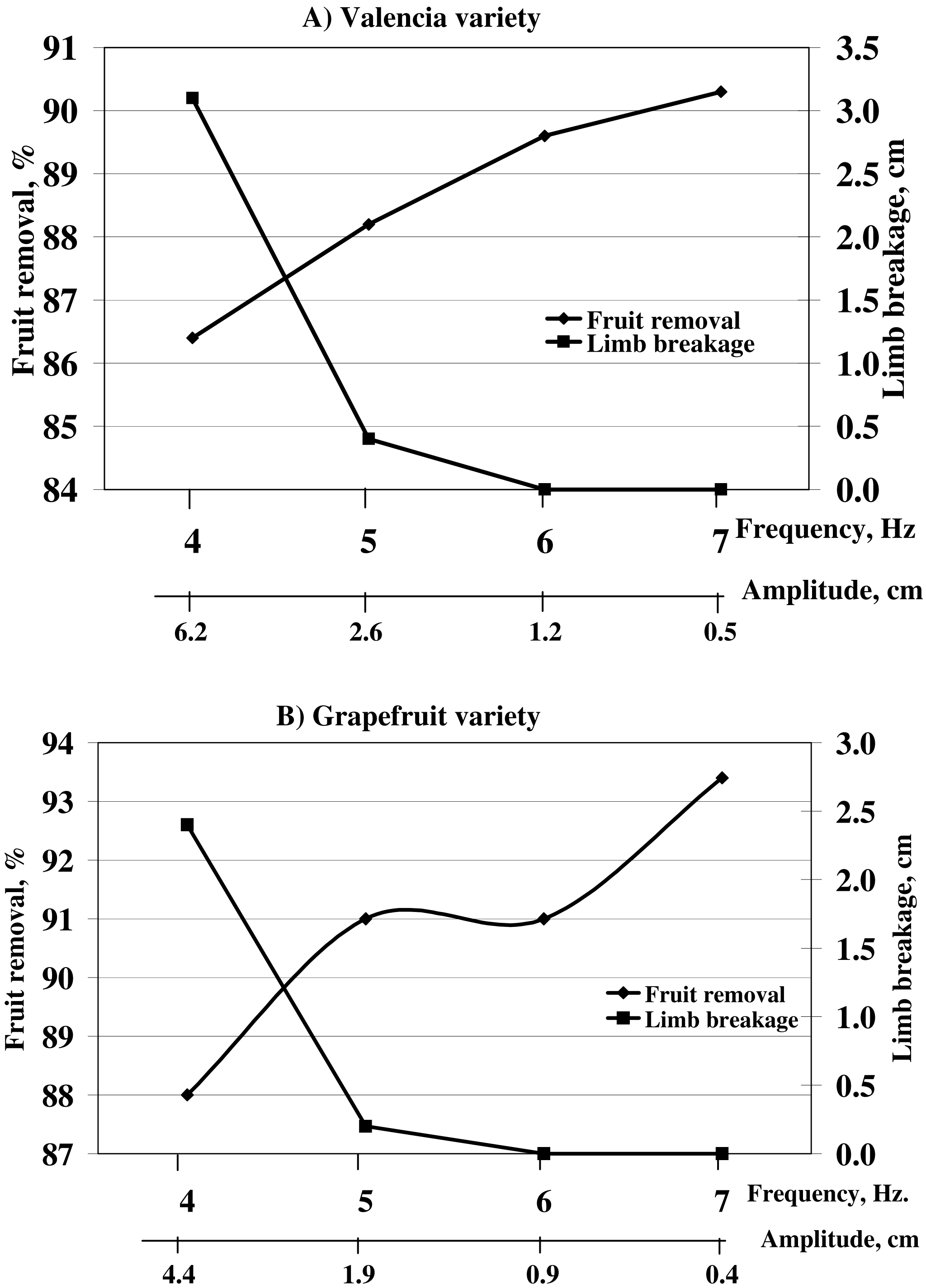


Fig. 3. Effect of frequency and amplitude on the fruit removal and limb breakage.

At all tested frequencies and amplitudes there were ns damages on the limbs at the point of contact of the clamp that reached the mentioned level of 3.6 cm^3.

4.3. The effect of frequency and amplitude on the breakage of the limb

Based on the information of horticulture specialist, any noticeable breakage in the limb is considered harmful consequently; it may affect the water and nutrient movements from the main trunk to the limb and fruits.

For Valencia variety, the values of limb breakage are shown in fig. 3-A. It is clear that the maximum value of limb breakage was 3.1 cm at amplitude 6.2 cm and frequency 4 Hz. From fig. 3-A it can be seen that by decreasing amplitude less than 6.2 cm, the breakage of limb was decreased.

For Grapefruit variety, the values of limb breakage are shown in fig. 3-B. It s clear that the maximum value of limb breakage was 2.4 cm at amplitude 4.4 cm and frequency 4 Hz. From fig. 3-A it can be seen that by decreasing of amplitude less than 4.4 cm, the breakage of limb was decreased.

From figures (3 A and B) it is clear that the breakage of Valencia and Grapefruit limbs may be caused by applying excessive amplitude.

From figures (3 A and B) it is clear that the optimum citrus fruit removal percentage without limb damage can be realized when shaking is applied at 0.4 to 1.2 cm amplitude and 6 to 7 Hz frequency. For these conditions 89.6 to 93.4 % removal percentage was achieved without limb damage and breakage.

CONCLUSION

From this investigation, the following conclusion can be made:

1. The mathematical derived equation can be used with enough confidence in predicting the shaking amplitude for shaking machine.
2. The detachment force of Valencia variety decreased by 22.7 and 27.2 % with the increasing of maturity. While the detachment force of Grapefruit variety decreased by 40.6 and 52.1 % with the increasing of maturity.
3. The damping ratio at any ripening stage was 0.106 and 0.132 for Valencia and Grapefruit respectively.
4. The suitable values of amplitude for Valencia and Grapefruit varieties ranged between (6.2 to 0.5 cm) and between (4.4 to 0.5cm) respectively.

5. The fruit removal percentage increased by small percentage when the frequency increased from 4 Hz to 7 Hz
6. Applying excessive amplitude may cause breakage of citrus limbs.

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الملخص العربى

التنبؤ بطول المشوار المناسب لوحدة الهز عند حصاد ثمار الفاكهة

محمد إبراهيم غنيمي *

تم عمل تحليل رياضي أعتمادا علي معادلة La Grange باعتبارها معادلة أتزان الطاقة لاي منظومة اهتزاز، لاستنتاج علاقة رياضية تربط بين العوامل المؤثرة على الحصاد الميكانيكي لثمار الفاكهة باستخدام اسلوب هز الفرع للتنبؤ بطول المشوار المناسب لوحدة الهز.

و قد أوضحت العلاقة المستنتجة أن طول المشوار يعتبر دالة في كل من نسبة القوه اللازمة للفصل إلى كتلة الثمرة (F/m) و طول عنق الثمرة (ℓ) و التردد (ω) و أيضاً نسبة التثبيط (ζ).

و قد تم إجراء دراسة معملية لتقدير تلك العوامل التي تؤثر على تقدير طول المشوار المناسب لحصاد صنفين من أصناف الموالح و هما البرتقال الصيفي و الجريب فروت و كذلك تم إجراء دراسة حقلية لتقدير النسبة المئوية للثمار المفصولة و كذلك التلف الحادث للفرع. و قد تم اختبار أطوال المشاوير المناسبة من المعادلة و كان ٠,٥، ١,٢، ٢,٦، ٦,٢ سم لصنف البرتقال الصيفي و ٠,٤، ٠,٩، ١,٩، ٤,٤ سم لصنف الجريب فروت و المناظرة للترددات ٧، ٦، ٥، ٤ هرتز على الترتيب عند زمن هز مقداره ١٠ ثانية.

و قد بينت الدراسة ما يلي:

١. تقل القوة اللازمة للفصل لصنف البرتقال الصيفي و صنف الجريب فروت بنسب تراوحت من ٢٢,٧ إلى ٢٧,٢ % و ٤٠,٦ إلى ٥٢,١ % على الترتيب نتيجة زيادة درجة النضج.
٢. كانت قيم نسبة التثبيط لأي مرحلة من مراحل النضج هي ٠,١٠٦ و ٠,١٣٢ لصنف البرتقال الصيفي و الجريب فروت على الترتيب.
٣. تراوحت قيم النسبة المئوية لفصل الثمار ما بين ٨٦,٤% إلى ٩٣,٤% للترددات و المشاوير المختبرة لأصناف الموالح محل الدراسة.
٤. يزداد الضرر الحادث للفرع عند نقطة اتصال الفرع بالجذع معبراً عنه بعمق الكدمة بزيادة طول المشوار.
٥. لم يحدث أي ضرر للفرع عند نقطة الاتصال مع ماسك ماكينة الحصاد.

و نستخلص مما سبق أن المعادلة المستنتجة يمكنها التنبؤ بطول المشوار المناسب لهز فروع أشجار الموالح نظراً لزيادة نسبة الثمار المفصولة (من ٨٦,٤ إلى ٩٣,٤%) مع تلاشي التلف الحادث للفرع.

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