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Design, Construction, and Evaluation of a Shaking Track Equipped with Flexible Arms

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ABSTRACT

This study was conducted to design, construct, and evaluate a vibratory apple harvesting machine. The natural frequency, damping constant, damping coefficient, and stiffness of the branch are determined based on its mechanical properties. In the next step, to evaluate the efficiency of the machine in terms of apple detachment, a factorial experiment (3 × 3) with a completely randomized design was conducted to investigate the amplitude and frequency for apple detachment. Three levels of frequency (4, 9, and 20 Hz) and three levels of amplitude (20, 32, and 40 mm) were investigated. Analysis of the variance of fruit detachment based on Duncan 5% shows that shaking frequency and shaking amplitude both have a highly significant effect on fruit detachment. The effects of shaking frequency and amplitude were both significant on fruit detachment, but no interacting effects were observed. The most suitable shaking frequency and amplitude for harvesting apples were 9 Hz and 40 mm, respectively, which resulted in a 94.37% fruit detachment rate. The static pulling force required to detach the fruit from the branch decreases with an increase in fruit mass or geometric size. The ratio of the static detachment force to fruit weight was determined to vary between 5.1 and 15.3 for the apple investigated. Therefore, in apple harvesting, the effect of increasing the shaking amplitude relative to the shaking frequency on fruit detachment was concluded. Applying oscilation for 8 seconds increased harvesting, but increasing the time from 8 seconds to above, that did not significantly affect the outcome.

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Introduction

Firebank (1946) was the first to try mechanizing fruit tree harvesting. He used a unique rotating mechanism. A cable attached to the tree branch helped him harvest walnuts. Loghavi et al. In 2010, a tree shaker was designed. It features a mechanism for variable amplitude and speed. This device is used to harvest Estahban figs. To evaluate this machine, use a vibration frequency of 10 Hz and an amplitude of 45 mm. This setup can help harvest 93% of ripe fruits [1]. Du et al. In 2014, researchers explored how tree structure affects resonant frequency and vibration response in mechanical applications. They found a frequency of 14 Hz for harvesting cashew nuts. This takes into account chain nodes and uniform branch diameters [2]. Rezaei et al. In 2016, researchers tested wild almond harvesting. They used a shaking device set to 16 Hz frequency and 5 cm amplitude. The vibration lasted for 5 seconds. A logic controller helped adjust the settings to achieve about 90% efficiency [3]. Wang et al. In 2017, researchers explored how trees react to vibration. They used the finite element method for this study. They found that the vibration frequency depends on tree shape. Also, the vibration is absorbed where the branch meets the trunk [4]. Zhang et al. In 2017, researchers viewed the apple fruit-stem system as a pendulum. They applied torque at the branch's attachment point. They discovered that the stem acted like a rigid pendulum. Bending mainly happened at a vibration frequency of 0.85 times the fruit's natural frequency. In this study, about 90% of the fruits were harvested at a vibration frequency of 20 Hz for a period of 5 seconds [5]. Liu et al. (2018) studied apple harvesting methods. They found that using mechanical vibration with a variable frequency works best. It has high efficiency when the frequency changes from 8 Hz to 12 Hz [6]. Wang et al. (2019) conducted experiments on apple trees. Attaching the shaking arm farther from where the branch meets the trunk gives the best apple harvesting efficiency. This occurs at an amplitude of 14 mm and a vibration frequency of 16 Hz [7]. To increase harvesting efficiency and reduce damage to tree branches, Du et al. (2020) proposed a three-dimensional vibrating mechanism based on the branch vibration model. The main feature of this shaker was the presence of a hydromotor and a hydraulic cylinder. The results showed that when the hydromotor rotates at a speed of 470 rpm, 76.5% of the fruits are harvested within 10 seconds [8]. Zhang et al. (2020) found the natural and resonant frequencies of apples. They also created a smart robot with a vibration mechanism. In this machine, using smart sensors [9]. High-frequency vibrations (25-40 Hz) with low amplitude (20-25 mm) aid in harvesting various fruit trees. This is especially true for trees with hard branches and low flexibility. For flexible branches or tall trees, vibration affects harvest rates the most. This happens when the amplitude is high (100-125 mm) and the frequency is low (1.5-6 Hz) [10]. Pole shakers had benefits, like needing just one operator. But their high cost and frequent breakages made them less popular [11]. Mechanical fruit harvesting saw major advancements in the late twentieth century. By the early 1930s, progress moved fast. This led to using forced vibrations for harvesting [12].

Golpira and Laghvi (2022) created a prototype of a tractor-mounted truncheon. This device is meant for harvesting olives. This device had an eccentric weight that rotated around a common axis. The rotation of the weights was provided by the tractor's (PTO) and through a belt drive system. The harvesting efficiency was evaluated as 95% at a frequency of 10 Hz and an amplitude of 80 mm [15]. Niu et al. In 2022, researchers studied how a system of fruit and stem vibrates. They used finite element methods for their analysis. This experiment studied an olive tree. Researchers found that when the tree vibrates close to its resonance frequency, it hits a state of resonance. This state helps separate the fruit from the branch [16].

Methodology

We used vibration models to design and build the device. This included the branch model and two mass models for the eccentric weights. First, we measured the branch's natural frequency, damping coefficient, and stiffness. Then, we designed the device.

Calculating the natural frequency of apple

Diagnostic and statistical calculations related to vehicles are significant applications [17]. To calculate the natural frequency of vibration, the branch was placed in a single-ended beam position, a stabilizing pen was attached to the end of the branch, and a cardboard plate conducted by brushed dc motor which was kept in contact with the pen. Figure 1(a). The branch was stretched until it reached its ultimate elastic limit and released. During the vibration of the branch, the cardboard plate was moved along at a speed of 1 m/s [18]. The branch's vibration and the cardboard's movement created a sine wave, shown in Figure 1(b). We measured the number of oscillations over time to calculate the natural frequency. In this experiment, the natural frequency of the apple branch was calculated to be about 12 Hz. Given that for small changes in position in pendulum motion with a double pendulum, the motion can be simulated with a single degree of freedom system, in this study, the damping coefficient was calculated using the formula (1,2) [18, 19].


(a)

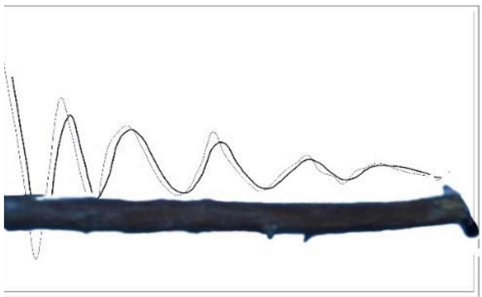
(b)

Figure 1. a) Creating a vibration diagram b) The wave resulting

$$\delta = \frac{1}{n-1} ln \frac{x_1}{x_2} \quad (1)$$

$$\xi = \frac{\delta}{2\pi} = \frac{c}{2mf} \quad (2)$$

In equation (1), X1 is the amplitude of the first wave formed due to the vibration of the branch, Xn is the amplitude of the nth wave formed due to the vibration of the branch, $\mathcal{F}$ the natural frequency is in Hz, ξ the damping coefficient is, c the damping constant of the branch is in kilograms per second, and δ the displacement of the branch is in meters. By recording the values of $x_1 = 28$ and $x_2 = 5$ mm and the number n = 10 and using equations (1) and (2), the branch displacement was calculated to be 0.145 and the damping coefficient was calculated to be 0.025. The damping constant was determined using the damping coefficient equation (2) and the following equation:

$$\xi = \frac{c}{2mf} \Rightarrow 0.03 = \frac{c}{2 \times 5 \times 9} \Rightarrow c = 3.6kg/s$$

Branch stiffness coefficient

In the field of vibration and design, it is necessary to determine the stiffness coefficient (k). To determine (k) it is sufficient to consider the branch homogeneously as a cantilver beam. To calculate this coefficient, a spring force gauge, Figure 2, was employed. By pulling the branch in two directions perpendicular to the branch [13], a force of 101.5 N was required to achieve a displacement of 0.145 m [13]. Thus, k equals 700 N/M.

$$\delta = \frac{FL^3}{3EI} \tag{3}$$

$$k = \frac{F}{\delta} \tag{4}$$

Figure 2. **Force gauge to measure the static force to separate fruit**

Vibrational motion model

We begin by creating a vibrational motion with weights outside the center Consider the vibrational equation of a mass that is weighted and located at a distance from the membrane, rotating at an angular velocity, as shown in Figure 3(a). [21]. given the Figure 3(a) the distance X & Y, it can be calculated based on trigonometric equations from equations (5) and (6). Given that acceleration is the second derivative of displacement with respect to time, in other words $a = \frac{d^2x}{dt^2}$, acceleration in the equivalent direction x equivalent $(-\omega^2 r \cos \omega t)$ and acceleration in the equivalent direction y are obtained $(-\omega^2 r \sin \omega t)$, respectively. By substituting these values into the relationship (F = ma) in the directions x and y, equations (7) and (8), is obtained.

$$x = r \cos \omega t \quad (5)$$
$$y = r \sin \omega t \quad (6)$$
$$F_x = m\frac{d^2x}{dt^2} = -m\omega^2 r \cos \omega t \quad (7)$$
$$F_y = m\frac{d^2y}{dt^2} = -m\omega^2 r \sin \omega t \quad (8)$$
$$\omega_1 = \omega_2 = \omega$$

The limitation of using this method can be the lack of control for the vibration, which causes great damage to the branch of the tree. To overcome this problem and control for vibration, two weights can be used outside the center of materials as shown in Figure 3(b). In this calculation, mass M is assumed to be very large. Using the single-mass vibration equations, we can achieve the following solutions [21].

$$\sum F_x = m\frac{d^2x}{dt^2} = -m_1\omega_1^2 r_1 \cos(\omega_1 t) - m_2\omega_2^2 r_2 \cos(\theta - \omega_2 t) \quad (9)$$
$$\sum F_Y = m\frac{d^2y}{dt^2} = -m_1\omega_1^2 r_1 \sin(\omega_1 t) - m_2\omega_2 r_2 \sin(\theta - \omega_2 t) \quad (10)$$

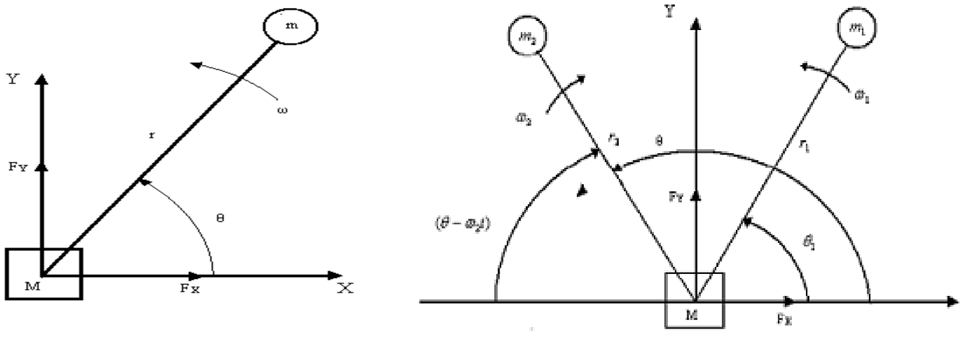

Figure 3. a) Single mass motion b) Reverse rotation of two eccentric weights [21]

Considering the equations if $\omega_1 = \omega_2 = \omega, r_1 = r_2 = r, m_1 = m_2 = m$ and also $\theta = \pi$ the following results are obtained:

$$\sum F_X = 0 \quad (11)$$
$$\sum F_y = -2m\omega^2 r \sin(\omega t) \quad (12)$$

As can be seen from equations (11) and (12), the sum of forces in the X direction is zero. In other words, the forces are balanced in this direction. Now, if we divide the sum of forces in the direction of y by mass M and integrate it twice, we obtain the displacement y from the following equation.

$$y = \frac{2mr}{M}\sin(\omega t) \quad (13)$$

Also, the displacement of the center of mass M can be obtained by integrating two times from equations (9) and (10). Equations (14) and (15) are obtained.

$$x(t) = \left(\frac{m_1}{M}\right) r_1 \cos(\omega_1 t) + \left(\frac{m_2}{M}\right) r_2 \cos(\theta - \omega_2 t) \quad (14)$$

$$y(t) = \left(\frac{m_1}{M}\right) r_1 \sin(\omega_1 t) + \left(\frac{m_2}{M}\right) r_2 \sin(\theta - \omega_2 t) \quad (15)$$

Vibrational branching equation

The vibrational equation of the branch is shown below in Figure 4, [20, 21].

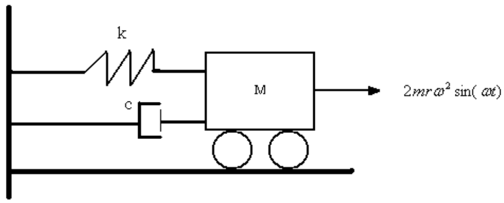

Figure 4. Shaking vibration branch modeling [20, 21]

Relations (16) and (17) are used to express the vibrational branching equation.

$$F = ma \quad (16)$$

$$M\frac{d^2y}{dt^2} + c\frac{dy}{dt} + ky = 2mr\omega^2 \sin(\omega t) \quad (17)$$

In this relation, C is the damping coefficient in Newton seconds per meter and k is the stiffness in Newtons per meter. Equation (18) is obtained by solving the second-order equation (17):

$$y(t) = \frac{2mr\omega^2}{[(k - M\omega^2)^2 + (c\omega^2)]^{0.5}} \sin(\omega t - \alpha) \quad (18)$$

$$\alpha = t\,an^{-1}\left(\frac{c\omega}{k - \omega^2}\right) \quad (19)$$

If the natural frequency is defined as $\omega_n{}^2 = k/M$ and the damping ratio is defined as $\xi = c/(2M\omega_n{}^2)$, by substituting the natural frequency and damping coefficient in equations (18) and (19), equations (20) and (21) are obtained [20, 21]:

$$y(t) = \frac{\frac{2mr\omega 2}{k}}{\left\langle\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 2\left(\frac{\xi\omega^2}{\omega_n}\right)\right\rangle^{0.5}} \sin(\omega t - \alpha) \quad (20)$$

$$\alpha = tan^{-1}\left\langle\frac{\frac{2\xi\omega}{\omega_n}}{1 - \left(\frac{\omega}{\omega_n}\right)^2}\right\rangle \quad (21)$$

As shown in Equation (21), the phase α is only a function of the ratio of frequencies and the dip ratio and can be plotted as Figure 5, 6. These curves show that in the region of near-excited frequencies, damping has a great effect on the amplitude and phase angle of the phase [20].

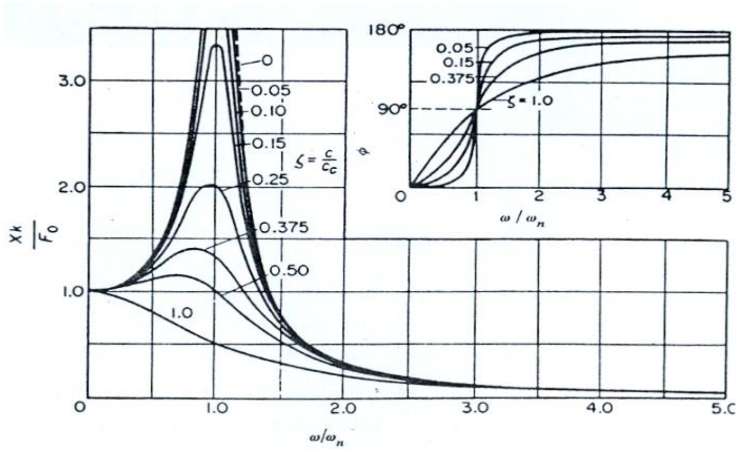

Figure 5. Vibrational equation curve for frequency ratio [20]

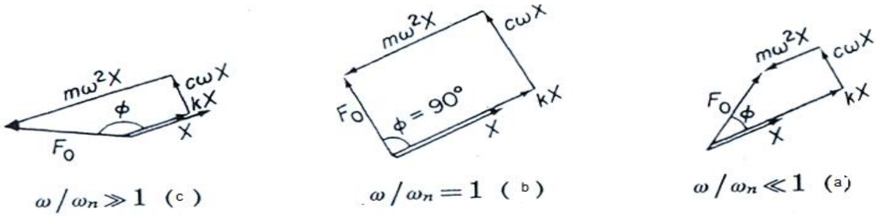

Figure 6. Communication in forced vibration [20]

Determination of power consumption

The equation (22) [13, 14] is used to calculate power consumption.

$$P(t) = F(T).V(T) \quad (22)$$

So, with a one-time derivation of equation (6) and assuming that $\omega \gg \omega_n$ we get the relation (23):

$$\frac{dy}{dt} = \frac{2mr\omega}{M}cos(\omega t) \quad (23)$$

By multiplying the relation (19) with relation (6), we obtain the instantaneous power relationship (24)

$$P_{inst} = [2mr\omega^2 \, sin(\omega t)]\left[\frac{2mr}{M}cos(\omega t - \alpha)\right] \quad (24)$$

To obtain maximum power, it is sufficient to derive the equation (24) relative to time and make it equal to zero.

$$\frac{dP_{inst}}{dt} = [2mr\omega^3 \, cos(\omega t)]\left[\frac{2mr}{M}cos(\omega t - \alpha)\right] - [2mr\omega^2 \, sin(\omega t)]\left[\frac{2mr\omega}{M}sin(\omega t - \alpha)\right] = 0$$

By solving the trigonometric equation mentioned above, we obtain the answer (25)

$$t = \frac{\left(\frac{\pi}{4} + \frac{\alpha}{2}\right)}{\omega} \quad (25)$$

By replacing the relation (25) in equation (24) with relation (26), we can calculate the maximum power.

$$P_{inst} = \frac{4m^2r^2\omega^2}{M} sin\left(\frac{\pi}{4} + \frac{\alpha}{2}\right) \cdot cos\left(\frac{\pi}{4} - \frac{\alpha}{2}\right) \quad (26)$$

$$P_{inst} = \frac{4 \times (8)^2 \times (0.13)^2 \times (2 \times \pi \times 20)^2}{50} \times sin\left(\frac{\pi}{4} + \frac{0.52}{2}\right) \times cos\left(\frac{\pi}{4} - \frac{0.52}{2}\right) = 1.6\ Kw$$

The average power of the system for designing a power transfer system is calculated from the equation (27):

$$P_{avg} = \frac{1}{T_f}\int_0^{T_f} P_{inst}\, dt \quad (27)$$

$$P_{avg} = \frac{1}{T_f}\int_0^{T_f} [2mr\omega^2 sin(\omega t)]\left[\frac{2mr}{M} cos(\omega t - \alpha)\right] dt$$

The final result of the average power is relation (28):

$$P_{avg} = \left[\frac{2m^2r^2\omega}{M}\right] sin(\alpha) \quad (28)$$

$$P_{avg} = \left[\frac{2 \times (8)^2 \times (0.13)^2 \times (2 \times \pi \times 20)}{50}\right] sin(0.52) = 0.6\ Kw$$

Determine the torque to be consumed

The maximum torque used in the design is calculated using equation (29):

$$T_{max} = \frac{P_{max}}{\omega} \quad (29)$$

$$T_{max} = \frac{1.6 \times 1000}{2 \times \pi \times 20} = 12.7\ N.m$$

Determine the angle between force and displacement

The calculation of the difference between force and displacement is done according to relation (21):

$$\alpha = tan^{-1}\left\langle \frac{\frac{2\xi\omega}{\omega_n}}{1 - \left(\frac{\omega}{\omega_n}\right)^2} \right\rangle$$

$$\alpha = tan^{-1}\left\langle \frac{\frac{2 \times 0.03 \times (2 \times \pi \times 20)}{(2 \times \pi \times 12)}}{1 - \left(\frac{(2 \times \pi \times 20)}{(2 \times \pi \times 12)}\right)^2} \right\rangle = 0.52\ rad$$

Fruit drop percentage

By applying vibration to the branch, shaking it at a certain amplitude and frequency, some of the fruits separated from the tree(x), while some remain on the branch (y). The percentage of fruit loss pr was calculated by separating the remaining fruits on the branch and weighting both groups using the following equation (30).

$$p_r = \frac{x}{x+y} \tag{30}$$

The force required to separate the fruit

To measure the force required before shaking the tree with a shaking branch, 27 apples were randomly tested. The method was as follows: special force gauge clamps (Figure 2) were attached to the fruit and the force gauge was pulled along the fruit's stem until the fruit was separated from the stem or from the junction of the stem and branch. The force shown by the force gauge was determined as the force required to separate the fruit from the tree in a static state.

Geometric mean diameter

Using a caliper, measure the lateral dimensions of the apple in three perpendicular directions and calculate the geometric mean diameter (31).

$$d = (a \cdot b \cdot c)^{\frac{1}{3}} \tag{31}$$

Test method

The first step in creating the vibration mechanism was a mechanical design using SolidWorks software. In this scheme, as shown in Figure 7. A mechanism should be made to move the two off-center weights in the opposite direction. SolidWorks software designed the mechanism for moving off-center weights. It helps create parts and models for simulation and dynamic analysis. Self-aligning bearings were chosen for the system. This choice resulted from the noticeable vibration and the alignment of the transmission shafts. This mechanism was placed inside a cube-shaped box figure 8 with a shocking arm. The branch connecting the shock arm to the vibration box was found and vibrated. The arm is telescopic, so it can change length. This mechanism lets the branch bend toward the vibrating box. It can fit between the box and the arm. To protect the tree bark, we added a rubber cushion where the branch meets the arm. Moving the weights affects the amplitude of the oscillation. It shifts toward the center of the plates. As can be seen in the image, a weight is placed on each side of the plate. The goal of this work was to keep the plates balanced. We used their moment of inertia to store energy and reduce vibration. The swing arm required a floating mechanism. It also needed to support the vibrating box and the swinging arm consistently. Thus, the mechanism of Figure 9 was designed. The pendulum system stops vibrations from reaching the arms and the tractor. We created a rotating support arm. It allows the flexible arms to turn around the device's vertical axis. Figure 9.

Figure 7. Vibration mechanism

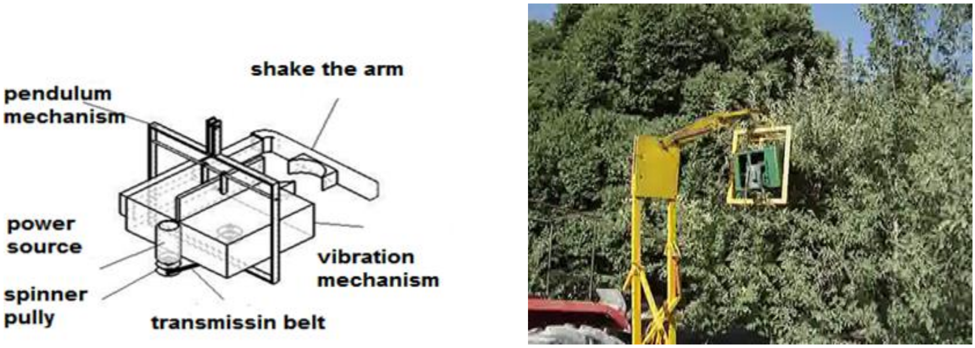

Figure 8. Vibration mechanism for transfer vibration to stem

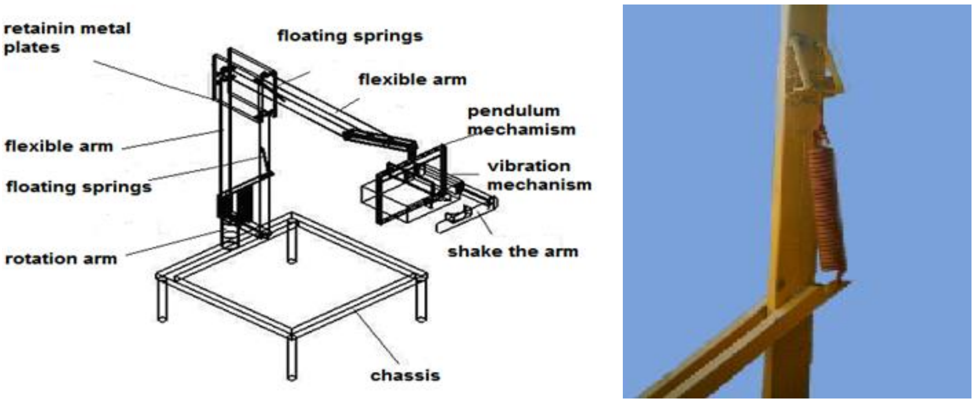

Figure 9. Floating and rotating mechanism

Results and discussion

In this study, a factorial experiment was used in a completely randomized design with 9 treatments (3×3) in 3 replications. For this purpose, 27 apple trees were selected for the experiment. This number was randomly placed in three groups of 9. Each group, which formed one replication, consisted of 9 treatments, and each treatment included a random combination of an amplitude (s1 to s3) and a frequency (f1 to f3). Each tree contained only one frequency level and a specific oscillation amplitude, and these two levels were tested with 3 replications. We collected data and calculated the fruit harvest percentage. This was done for different amplitude and frequency values in apple harvesting. To improve accuracy, we used MSTATC software. The variance results are shown in Table 1. The analysis of variance table for apple irradiation shows that 99% of the differences in amplitude and frequency levels greatly impact fruit detachment. Besides, this table implies that the interaction between these two factors is not meaningful.

Effects of different amplitude and frequency on fruit harvest percentage

The experiment was conducted in October at a temperature of 20°C and a humidity of 14%. We studied how amplitude and frequency impact fruit harvest percentage. We compared the treatment averages with the Duncan test. Table 1 shows the average fruit drop percentages for three treatments. It compares different amplitudes and frequencies at a 5% significance level. For fruit detachment, the results highly significant difference among different levels of oscillation frequency and amplitude, but the effect of the interactive of frequency and amplitude were not signigicant. Higher oscillation amplitudes at different frequencies cause a greater fruit drop percentage. More fruit drops happen when oscilation amplitude increases. This causes faster fruit acceleration. The increased acceleration causes the fruit to fall from the branch. Table 2 shows that increasing the oscillation frequency affects fruit drop less than boosting the oscillation amplitude. At higher frequency levels, significantly higher fruit detachment not occurs, while increasing the shaking amplitude at different levels of frequency has increased fruit detachment significantly with a 40 mm amplitude, the results were even better: 85.29% separation at 4 Hz and 94.37% at 9 Hz. While fruit separation increases at 20 Hz, it also leads to too much leaf loss and branch breakage. This makes the method unacceptable. At amplitudes of 20 mm and 40 mm, more fruit detached as the frequency increased. To harvest fruit correctly, choose an amplitude of 40 mm and a frequency of 9 Hz. This approach ensures good harvesting while minimizing damage to the tree. Figures 10 and 11 show fruit separation in different amplitudes and frequencies. The two diagrams show that both the amplitude and frequency of fruit detachment are up. The rise in amplitude affects the percentage of fruit detachment more.

Table 1. Analysis of variance in different amplitude and frequency

Source of change	Degrees of freedom	Sum of squares	Mean square	F_S	F 5%	F 1%
Amplitude	2	459.360	2299.680	37.05$^{\times\times}$	3.63	6.23
Frequency	2	844.823	422.411	28.8943$^{\times\times}$	3.63	6.23
Reciprocal effect	4	61.754	15.438	1.0560$^{n.s}$	3.01	4.77
Test error	16	233.907	14.619			
Total	26					

××-The existence of a significant difference with a probability of 99%
n.s-No significant difference

Table 2. Mean Comparison in different of main effects (Amplitude, Frequency) and their interaction (Duncan 5% test)

Ampliude (mm) / Frequency (Hz)	20	32	40	Mean
4	51.64 g	73.13 de	85.29 b*	70.02 C
9	63.35 f	77.56 cd	94.37 a	78.42 B
20	68.71 ef	82.15 bc	99.93 a	83.60 A**
Mean	61.23 C	77.61 B	93.20 A	

* -lowercase letters indicate comparison of interaction effects (Amplitude×Frequency). Means sharing the same lowercases letters are not significantly different the 5% level.
** -Uppercase letters indicate comparison of main effects (Amplitude or Frequency). Means sharing the same uppercase letter are not significantly different at the 5% level.

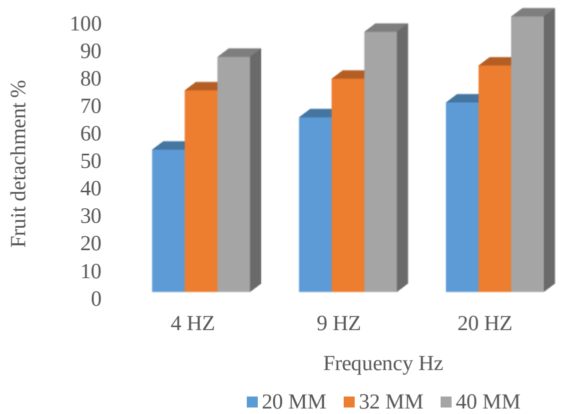

Figure 10. Effect of amplitude on costant frequency

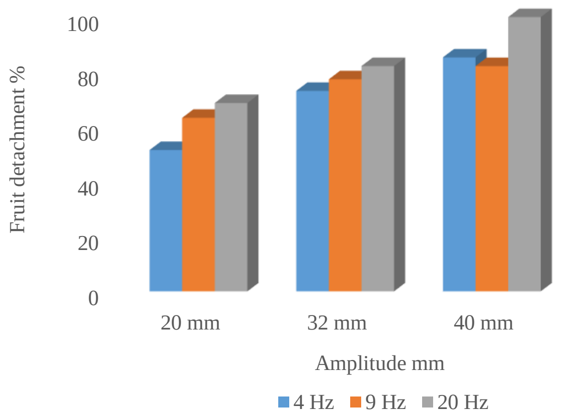

Figure 11. Effect on frequencies on constant amplitude

Figure 12 shows the fruit falling at a constant frequency. Figure 13 shows the fruit falling with a constant amplitude. In Figure 12, the fitting lines are close together. In Figure 13, the lines are spaced apart. This shows that amplitude affects the percentage of fruit loss more. In Figure 12, we assume a constant frequency for each line. So, the amplitude should then increase. For example, if the machine runs at a steady 4 Hz and a 20 mm amplitude, we can see the line on the graph. This helps us find the percentage of fruit detachment. In this case, the fruit detachment is 51.64%. If we raise the amplitude from 20 mm to 32 mm at a steady frequency of 4 Hz, the fruit falling rises by 61.41%. This brings the total to 73.13%.

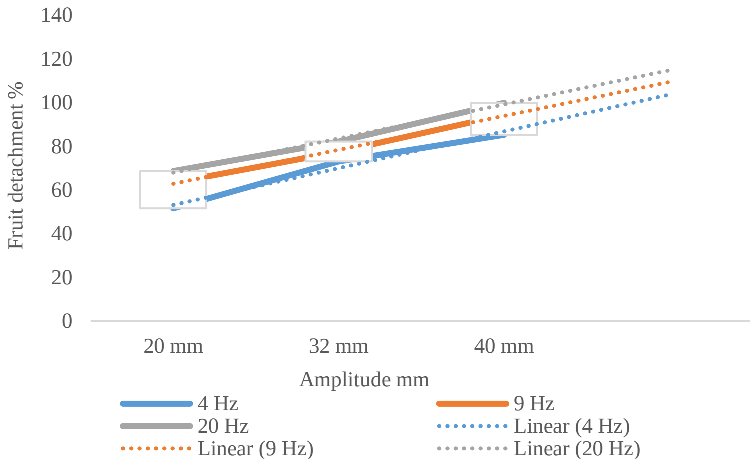

Figure 12. Percentage of apple detachment in a constant frequency

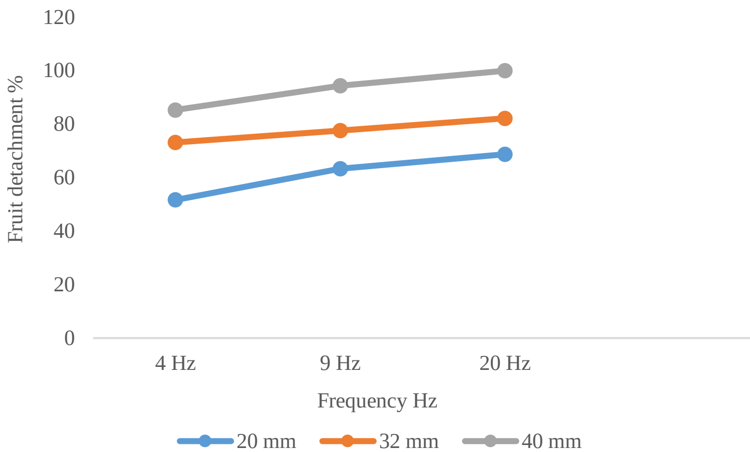

Figure 13. percentage of apple detachment in a constant amplitude

The increase in amplitude to 40 mm results in a 65.16% increase in the percentage of apple fruit falling compared to the first case, i.e. Compared to the second case, the 20 mm amplitude increased by 67.16%. By increasing the frequency level, we will reach the 9 Hz frequency level. It is evident that the percentage of apple fruit falling increases with increasing amplitude on this line. For instance, if the amplitude increases from 20 mm to 32 mm, the percentage of fruit falling should increase by 22.43%. The result of all these observations is that the amplitude, regardless of the frequency changes, is an important and influential factor on the percentage of fruit drop, and at a fixed frequency level, the amplitude of fruit drop increases with increasing levels of different levels. Another issue that can be seen in this diagram is the distance between the lines drawn from each other. The distance between the 9 Hz frequency line and the 4 Hz frequency line undergoes an abrupt change, while the distance change between the 9 Hz and 20 Hz frequency lines is less noticeable. This can be explained by the fact that although the oscillation frequency plays a significant role in fruit separation, increasing the frequency level in accelerating the fruit for its separation to a certain extent can be effective, and increasing it excessively cannot have much effect on fruit fall. However, increasing the amplitude has a greater effect on the percentage of fruit drop than the frequency. This is clearly illustrated in Figure 13. The reason for this can be explained as follows: apple branches are flexible and curved branches and act as mechanical dampers and do not transmit vibration to the fruit-branch system, and the amplitude of the oscillation causes acceleration of the fruit. In Figure 12, three linear equations are obtained: Pr = 1.53S 36.79 for 20Hz frequency, Pr = 1.52S 1.52 for 9Hz frequency, and Pr = 1.69S 18.16 for 4Hz frequency, as shown. In every relationship that exists, the oscillation amplitude in millimeters and percentage of fruit yield are both expressed as percentages. The values R2 are expressed as 0.96, 0.99, and 0.97 for frequencies 20, 9 and 4 Hz respectively. From Figure 16, it can be deduced that by passing the closest regression line through the points in the diagram, three fitting lines are obtained, which indicates that as the amplitude of the fluctuation increases, the percentage of apple dropping also increases proportionally. Similar results were reported by Erdogan (2003) on apricot fruit, similar to Figure 13 is included containing these results [22].

Dynamic force acting on vibrating fruit

Fruits with loose connections are separated at lower frequencies, and those with tighter connections are separated at higher frequencies. The reason for this is that the dynamic force resulting from oscilation is proportional to the square of the vibration frequency and the first power of the amplitude. As frequency increases with a constant amplitude, the dynamic force acting on the fruit that causes it to separate increases. The equation [26] is used to determine the amount of dynamic force.

$$F = mr\omega^2 \quad (32)$$

Table 3 lists the physical properties of apples, including dynamic force in terms of (N), fruit mass in terms of (Kg), eccentricity, which is equal to half the amplitude in terms of (M), and frequency in terms of (rad/s). The geometric mean in this table is the cube root of three perpendicular diameters, and Table 4 exhibits the static force needed to separate apples, as measured by a spring force gauge (Figure 2). The average force exerted on the fruit in different combinations of amplitude and frequency of the oscilation is listed in Table 5 and shows that in most cases where the oscilation applied to the tree branches resulted in the separation of most of the fruits, the average dynamic force exerted on the fruit was greater than the average static force required to separate the fruit, but in some cases the dynamic force was less than the static force required. The possible cause of this phenomenon is that, firstly, in calculating the dynamic force, the fruit's amplitude is considered to be the same as the amplitude of the clamp's attachment point to the branch, while the fruit's amplitude may not be the same as the amplitude applied to the branch because, due to the oscilating motion of the branch, the fruit's amplitude may be several times the amplitude applied by the device.

Table 3. Average mass, average weight and other physical properties of apple

Type of fruit	Average fruit mass (m) gr	Average fruit weight (w) N	Geometric mean diameter of fruit (d) mm	F/W
Apple	50.1	0.49	53.13	10.2

Table 4. Static forces required to separate apples

Type of fruit	Static forces required to separate apple(F)		
	Mean (N)	Max (N)	Min (N)
Apple	5	7.5	2.5

Table 5. Average dynamic force on apples

Frequencies (Hz) / Ampliude (mm)	4	9	20
20	0.64	3.24	16.02
32	1.02	5.2	25.6
40	1.35	6.8	33.66

Secondly, applying stresses to the fruit tail, which causes fatigue of the fruit tail at its attachment point, which ultimately causes the fruit to separate from the branch, is not included in the calculation of dynamic force.According to Tables 2 and 5, in the 40 mm amplitude and 4 Hz frequency, where the average dynamic force was calculated to be 1.35 Newton, about 85.29% of the fruits were separated, and in the 20 mm amplitude and 4 Hz frequency treatment, where the average dynamic force was 0.64 Newton, which was less than 5 Newton, only about 51.64% of the fruits were separated.This is while the force applied to the fruit with a vibration frequency of 20 Hz and an amplitude of 32 mm was calculated to be 25.6 Newtons,which is approximately 5 times the static force required to separate the fruit, but the percentage of fruit falling in this case was much less than with an amplitude of 40 mm and a frequency of 4 Hz.The question that arises here is that even though the force applied to the fruit in the 20 Hz frequency and 32 mm amplitude treatment was approximately 15 times the force in the 4 Hz frequency and 40 mm amplitude treatment, why did the percentage of fruit fall decrease by about 3 percent?

Researchers such as Fridley (1971), Adrian (1966) and Diener (1965) have concluded that the amplitude of vibration of different points of the branch changes with the frequency of the contact point of the branch with the clamp [26]. Therefore, it can be said that fruits whose dynamic force is still less than the average static force required to separate the fruit from the tree, taking into account the above case and the effect of oscillatory stresses on the fruit tail, cannot be separated and remain on the branch.So the above question can be answered as follows: in the first treatment, probably due to the change in the vibration form, the amplitude of vibration at different points of the branch was reduced compared to the second treatment, even though the number of nodes along the branch increased, which will lead to a decrease in the amplitude of oscillation at other points of the branch. Another possibility is that the natural vibration frequency of the branch is closer to 4 Hz and at this frequency the resonance phenomenon has increased the amplitude of the branch oscillation and consequently the fruit separation force. Researchers have mentioned in their research that the amplitude of the oscilation of different parts of the branch is not the same as the frequency of the contact point of the branch with the clamp, but varies between 25-135% of the oscillation amplitude of the device or the contact point of the branch with the clamp [25]. Accordingly, if we apply a oscilation to the branch with an amplitude of 32 mm and a frequency of 20 Hz, the dynamic force exerted on the fruits located at different points of the branch will vary between 4.6-34.56 Newtons (25-135 percent of the average given in Table 5. So it can be said that fruits that have a dynamic force less than the average static force required to separate the fruit (this force has been calculated to be 5 Newtons for apples) cannot be separated and the fruit remains on the branch. The connection between certain fruits and the branch may be stronger due to physiological reasons. Due to the aforementioned reasons, some fruits are still on the branch. During vibration, smaller apples on the branch require a higher applied frequency to separate due to their high natural frequency, and if the applied frequency is lower than this value, the apples will remain on the branch. On the other hand, larger apples require a lower applied frequency due to their lower natural frequency, and if the applied frequency is higher than this value, the apples under vibration will continue to oscillate on the branch without being separated from the branch.

Within the tested range, amplitude had a greater influnce on fruit detachment are than frequency, likely due to its direct effect on fruit acceleration and stress distribution in the fruit-stem junctionThe relationship between the static force necessary for fruit separation and the fruit's weight is depicted in Figure 14. This diagram shows the relationship between static force and weight expressed as $F= 3.4911W-1.089$, in which W represents fruit weight in terms of Newton, and F indicates the required static force Fruit separation in Newton. The estimate for the value of R2 in this relationship is 0.94. The power relationship between weight and static force necessary for fruit separation has been expressed by other researchers using a commonly used method. For example, in AbunaJmi's (1999) research on dates, the relationship between the static force necessary for the separation of fruits and their weight is expressed as a power relationship [18]. Researchers have characterized the relationship between weight and static force needed to separate the fruit. For example, Mohseni Niari (2002), during his research on sour lemon, described the relationship between the static force required to separate fruit and its weight as a linear relationship. Golpira (1992) was one of the researchers who conducted research on olives and linearly harvesting this fruit, investigating the relationship between the static force needed to separate the fruit and its weight. Figure 15 shows the linear relationship between the required static force for apple separation and its weight, which is the form F= -5.33 W+9.15. The R2 value was estimated to be 0.873. By comparing two linear and power equations, it can be argued that the expression of the relationship between the strength of the fruit to the weight of the fruit as a power relationship, because of the higher value of R2, is more reasonable and more favorable. The fruits separated from the branch by vibration are divided into two with and without tail. After harvesting, fruit that has been separated from the tail must be separated by a worker or other machine to increase the cost. By separating the fruits with and without tails and comparing the number of each of them in comparison with the total number, the results of the test showed that about 58 to 69.6% of fruits were with tail and the rest were without the tail. The conclusion we can draw from this is that the fruit's attachment to the tail is stronger than the tail's attachment to the branch [23, 24, 26]. The volume of agricultural products plays a crucial role in packaging issues and related parameters, such as dimensions [27]. The relationship between the mean geometric diameter of the fruit and the static force was investigated through a graphical plot. This linear correlation is depicted in Figure 16. Bypassing the nearest regression line from the points in the graph, we obtain a linear equation F= -1.6d+86.8 that indicates the static force F necessary for separating the fruit and represents the mean geometric diameter d of the fruit in millimeters. The value R2 in this relation is 0.73. Plotting the relationship between the static force, fruit weight F/W, and average geometric diameter d of the fruit examined the relationship between the two. According to the chart, the F/W ratio decreases with an increase in d. This ratio can be portrayed as a linear curve. Figure 17 shows the relationship between F/W and mean geometric diameter. Bypassing the nearest regression line from the points in the graph, we obtain a linear relationship F/W= -0.36d +19.6, with a value R2 of 0.79 in this relation.

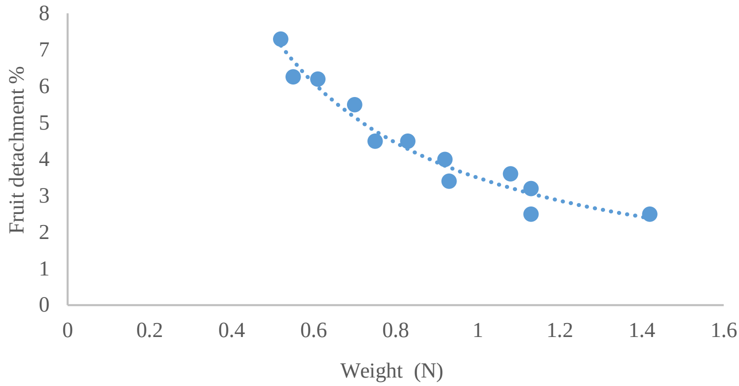

Figure 14. Static force for separation from the branch with weight

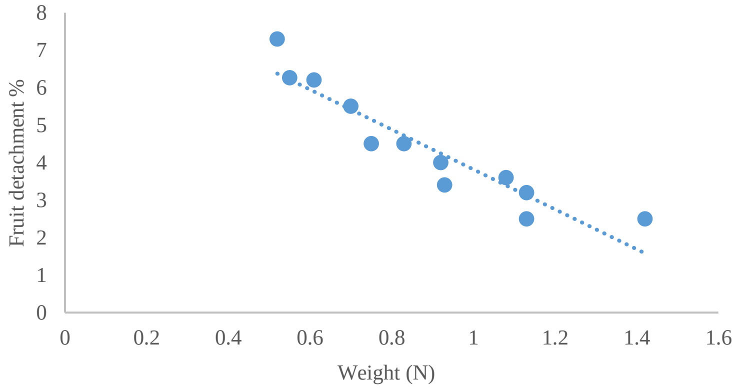

Figure 15. Static force for separation from the branch with apple weight

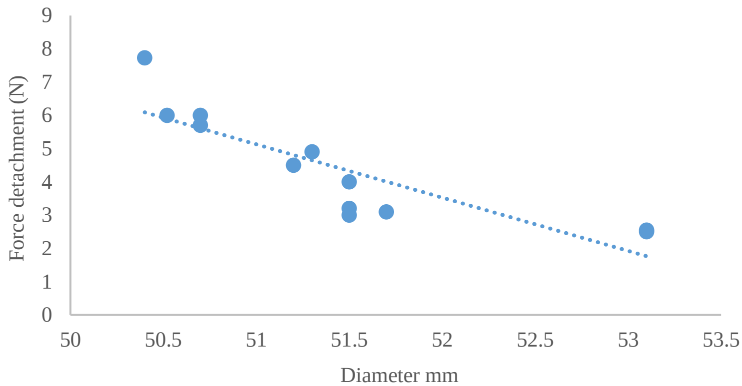

Figure 16. Force detachment from the branch with apple size

Effect of vibration time

The vibration time of the branch is a function of the damage to both the branch and the tree. As the vibration time increases, the loss of leaves increases and branches continue to break. Experiments showed that apple fruits dropped within the first few seconds, and the vibration continued to cause leaf loss and cracking of branches. This mode had a oscillation time of 10 seconds, a frequency of 25 Hz, and an oscillation amplitude of 40 mm. The data taken at the garden level of the test site enabled us to obtain Figure 18. In this diagram, as indicated, a regression line crosses the data entered in the chart, with the percentage of fruit detachment obtained being Pr=86.065-1.22t. The estimated R^2 value from the collected data was equivalent to 0.91. In order to minimize fruit loss and leaf fall, the ideal vibration time for apple harvesting was 8 seconds.

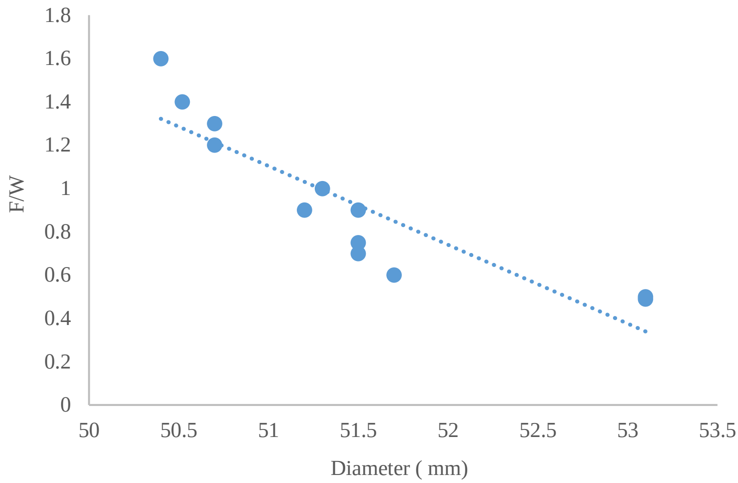

Figure 17. **Interpolation F/W with apple size**

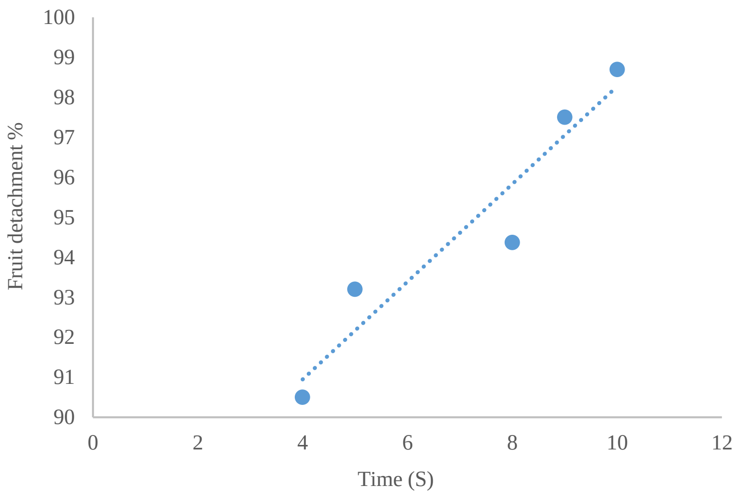

Figure 18. **The effect of vibration time on fruit detachment**

Conclusion

1- Both shaking frequency and amplitude had significant effects on fruit detachment at 8 seconds with the rate of fruit harvesting and the rate of leaf fall lowest, but there were no interacting effects observed.
2- The optimal harvesting parameters (9Hz, 40mm) achieved high efficiency (94.37%) with minimal damage, demonstrating the effectiveness of the flexible-arm design in transmitting while damping harmful forces.
3- As the mass or geometric size of the fruit increases, the static pulling force required to detach it from the branch decreases and the ratio it to the weight varies between 5.1 to 15.3.

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