Principles of a Mechanical Shaker for Coffee Harvesting

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ABSTRACT

Coffee harvesting is largely a manual operation, mostly done using hired labour, which may be expensive. The objective of this study was therefore to evaluate the possibility of using a power-take-off (PTO) driven mechanical shaker for coffee harvesting. In the theoretical analysis, a coffee tree was modeled as a cantilever beam with a concentrated mass at one end. The model tree was subjected to a damped forced vibration, to determine the optimal amplitude-frequency combination at which most coffee berries would be harvested. Experimental variables included the crank throw of the mechanical shaker at which the most berries were harvested and the duration of shaking beyond which there were few or no more berries harvested at constant PTO speed of 540 rpm, tree height and position of shaker attachment. The mass of individual berries and the resistance to detachment was also determined. It was found that the highest percentage of ripe coffee berries harvested was 45 %. A crank throw of 0.04 m was found to have the highest percentage of ripe berries harvested and beyond 10 seconds of exposure to mechanical vibration there were no more berries harvested. Optimal height for attachment of the mechanical shaker was found to be 0.6 m from the ground. It was also found that 1.2 N force was required to detach unripe berries and 0.9 N for the ripe and heavier berries. The force required to shake a single coffee tree was 12.8 N. The results indicate that the crank slider mechanism is suitable for use in coffee harvesting and that multiple coffee trees can be harvested simultaneously by a single for higher productivity.

Keywords: Mechanical shaker, coffee harvesting, crank slider mechanism, Kenya

1. INTRODUCTION

1.1 The Need for a Coffee Harvester in Developing Countries

Harvesting of Coffee is predominantly by hand-picking (Yayock *et al*, 1988). However, other methods that have been employed include; waiting for berries to drop to the ground and picking them thereafter, and beating berries off branches with long poles or stripping cherries together with leaves, followed by winnowing (Wrigley, 1988). These alternative methods to hand-picking are not only destructive but also reduce production, considering the importance of leaves for photosynthesis and flowers for development of the coffee berries.

In many cases, the high cost and short supply of labour may justify the desire for mechanical harvesters by many growers (Cargill, 1999). In the developing countries, labour may currently not be in short supply due to high rates of unemployment but is certainly expensive and could be better applied to other sectors of the economy. The Ministry of Agriculture in Kenya estimated that coffee harvesting required 1240 man-hours per hectare, equivalent to 0.28 man-hours per kg of cherries and 1.97 man-hours per kg of clean coffee. Picking alone accounts for over 75% of the labour requirement in coffee production (Ministry of Agriculture, 2002). Furthermore, manual labour requires high energy input compared to mechanized systems (Umar, 2003).

Spacing requirement for coffee plantations range from 1.0 m. to 4.5 m. (Coste, 2000), which can accommodate many types of machinery, including tractors and the auxiliary equipment. As such, many operations in the crop establishment such as spraying, cultivation and sub-soiling have been mechanized (Wrigley, 1988). Availability in the market of narrow tractors augment the possibility of mechanization in later stages of crop establishment.

With an average plantation area of 70 ha, Kenya has larger coffee estates than the major coffee producing countries in the world, such as Brazil and Costa Rica which have 60 ha and 30 ha, respectively (Wrigley, 1988). Despite the fact that cultivation of crops in large farms is usually an incentive for mechanization, coffee in Kenya is still harvested manually; hence, the potential for mechanization of coffee harvesting operation is enormous.

1.2 Mechanical Shakers

Mechanical shakers are large scale harvesting equipment with potential applications in wide range of fruits, berries and nuts. In general, harvesting equipment based on principles of a mechanical shaker consist of the shaker, collecting frame (catching units) and conveying devices, usually mounted on a self-propelled carrier, usually a tractor. The basic principle is to accelerate each fruit so that the inertia force developed will be greater than the bonding force between the fruit and the tree (Kepner *et al*, 1987). The excitation force is typically derived from cyclic oscillation of either a crank slider or two opposite rotating eccentric masses connected to the tree to be harvested (Thomson, 1988). The catching units used in shaker harvesting are collection surfaces below the shaker that extend under the tree covering the drop area of the detached fruits (Cargill, 1999).

Ripe and dry coffee berries are easier to detach than unripe berries, hence, in developing the principles for a mechanical shaker, it is necessary to determine the optimal mechanical parameters within which the resulting force will only harvest ripe and dry berries and leave unripe berries to reach maturity. The hypothesis adopted for this study was that the amount of coffee berries detached by exposure to mechanical vibration was mainly was mainly determined by the amplitude and frequency of the shaking, the height from the ground at which the tree is shaken, the height of the tree, the strength of bond between the berries and the tree, the duration of exposure to shaking and the mass of the berries. The primary objective was to develop a verifiable theoretical model that could be used to design a mechanical shaker for harvesting of coffee berries.

In mechanical harvesting of fruits and berries, it is common practice to apply the power source to shake one tree at a time (e.g. Brown et al, 1988; DenHartog, 1985; Graham 1996), which results in lower productivity and therefore a more expensive operation. This is not only time consuming but also expensive. Therefore a secondary objective of this study was to explore the possibility of handling multiple trees to enhance machine productivity.

2. LITERATURE REVIEW

2.1 Theory of Fruit Detachment by Shaking

Tsatsarelis (1987) presented a summary of the theories advanced by various researchers in an attempt to explain factors governing the detachment of fruit during harvesting by mechanical shakers. Emerging hypotheses are that:

1. Detachment is entirely governed by tensile forces acting on the fruit, and therefore occurs when the internal forces due to the motion of the fruit become greater that the static restraining forces;

2. Detachment is primarily due to bending forces, therefore, is caused by cumulative fatigue due to stress cycles, and occurs after a number of bending cycles. Otherwise, detachment is caused by the maximum relative bending between branch and stem or between stem and fruit;

3. Response of fruit-stem system to forced vibration is the key criterion, hence, the requirement to develop a realistic physical model of the fruit-stem system. The model response to forced vibrations is then determined.

The modeling approach is most versatile due to the fact that it is not restricted to the inherent mode of failure (Tsatsarelis, 1987), by developing a physical analogy and then seeking to determine the parameters influencing detachment, from the resulting mathematical models. It is for this reason that this approach was used in this research. Realistic models have been developed for other crops harvested by mechanical shaking (Affeldt-Jr. *et al*, 1989; Graham, 1996) but none has been developed for harvesting of coffee.

The concept of modeling a tree and tree parts as cantilever beams under vibration has been applied successfully in the development of a shaker for harvesting of dates (Abounajmi, 2000), by determining the tree natural frequency and the force required to shake tree limbs. Polat *et al* (2007) reported on the achievement of 95.5 % harvest rate through analysis of best frequency-amplitude combination for shaking in pistachio nuts. Other similar successful outcomes have also been reported by Erdogan *et al* (2003).

The effect of the application of circular and multidirectional vibrations to the trunk in the detachment of mature fruits of coffee was reported by Aristiz *et al* (2003) using coffee trees of *Caturra* and *Colombia* varieties. They showed that multidirectional vibrations were more effective, but better quality coffee (greater percentage of ripe berries) was obtained by circular shaking. Garcia-Uribe and Oliveros-Tascon (2003) showed that trunk shaking is a promising alternative for the selective mechanical harvesting of coffee; they observed that it was possible to detach more than 60 % of ripe coffee berries with less than 10 % immature coffee berries in the harvested mass in less than 15 s, which represents 6.3 % of the time required in manual picking, with insignificant tissue damage during the shaking process.

While there may be divergent views on the nature of forces that influence fruit detachment from the branches, there is a general agreement that amplitude and frequency affect the rate of detachment. All the papers reviewed by Tsatsarelis (1987) point to an amplitude-frequency combination at which the rate of removal is highest. This point is also called resonance and occurs when the frequency of excitations equal the natural frequency (Seto, 1994). Resonance varies with tree characteristics such as species, size, height and leaf density, hence, must be determined for each tree species.

2.3 Efficiency of Harvesting Fruits Using Mechanical Shakers

Efficiency in fruit harvesting refers to the percentage of ripe berries harvested. If there were 100 ripe fruits on a tree, and 60 fell when the shaker was applied, then the efficiency would be 60%. This is very easily understood for tree crops where ripening occurs at once. It is more confusing where there are both ripe and unripe fruits. In this case, still only the percentage of ripe berries is considered and the unripe ones are ignored completely as they are not considered useful. The instances cited in this section adopt this principle.

An efficiency of 66 % was obtained by Whitney & Harrel (1989) using long-stroke, low-frequency limb shakers for citrus fruits. However, efficiencies of 80-85 % were obtained with abscission chemicals. For apples (Patterson and Miller, 1989) the efficiency ranged from 85-95% for different apple varieties. Lang (1989) reported efficiencies between 94-97 % using a mechanical harvester developed by Lincoln Company.

Domingan *et al* (1988) observed that the major disadvantage of harvesting by mechanical shakers is the damage to fruits as they fall after they have been detached. However, this is not a problem for coffee since the product required is the coffee bean inside the fruit that cannot be damaged by impact on falling.

2.4 Coffee Harvesting Machines Available in the Market

Kuhn (2006) presented a range of coffee harvesting machines currently in use in Australia and Brazil. Harvesting in these machines is carried out by several vibrating fingers that disturb the coffee bush and cause the berries to fall. The falling berries are received in a conveying device where they are transported to a lorry trailing the harvester. All of the harvesters presented, are tall and large enough to cover the coffee trees to enable the small fingers to reach individual branches. They are all self-propelled machines and require the coffee trees to be planted in straight rows with utmost accuracy and pruned to specific height for efficient harvesting.

Barbosa *et al* (2005) evaluated the operational performance of some of these portable coffee harvesting machines and to evaluate the operational cost of the semi-mechanized harvest system in comparison to the system of manual harvest. They concluded that the semi-mechanized coffee harvester (and not the fully motorized machines) presented superior operational performance in comparison to manual harvest system, becoming a viable alternative for the small to medium size farmers in order to minimize the production costs.

Other problems that these tall and large machines face are their stability on sloppy terrain, particularly since coffee grows best in the highlands with such terrain. This is in addition to the fact that such machines may cause the development of hard pan by their heavy weight. These are some of the reasons that made it necessary to develop a system that is independent of the terrain, with minimal potential to cause compaction and which do not necessitate special pruning operations on the coffee stand.

3. THEORETICAL CONSIDERATIONS

The coffee tree attached to the crank-slider mechanism was modeled as a vibrating cantilever beam with a concentrated mass at one end as illustrated in Figure 1. The period (*T*) of any oscillating system or its natural frequency (ω_n) depend only on the mass (*m*) and stiffness (*k*) of the system, which are properties of the system.

$$\omega_n = \frac{1}{T} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (1)$$

A coffee tree being shaken by a mechanical shaker may be idealized as a cantilever beam under a concentrated load *m* at its center of gravity. The lateral deflection, $y(t)$, is obtained as shown in Figure 1.

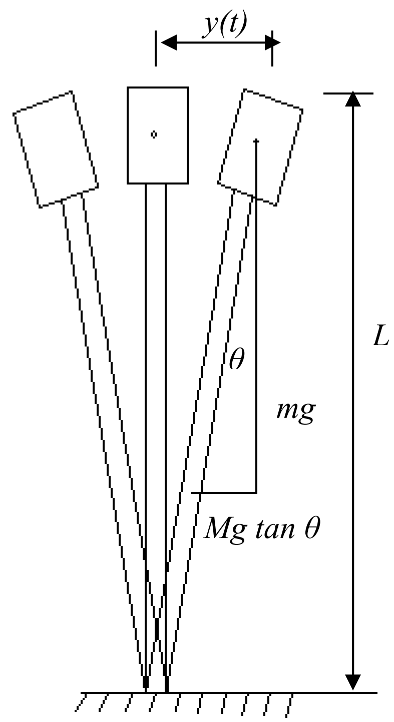

Figure 1. A coffee tree modeled as a cantilever beam with a concentrated mass at the top, indicating a lateral displacement, *y(t)*, due to excitation by a mechanical shaker

The natural frequency of the coffee tree modeled as a cantilever beam with a concentrated mass is obtained from:

$$\omega_n = \sqrt{\frac{3EI}{L^3} \cdot \frac{1}{m}} \quad \text{.......(2)}$$

Where:

- Second moment of area (I) of the circular coffee tree stem of diameter D is given by:
  $$I = \frac{\pi D^4}{64} \quad \text{.......(3)}$$
- E is the modulus of elasticity of the coffee tree stem
- L is the height of the coffee tree

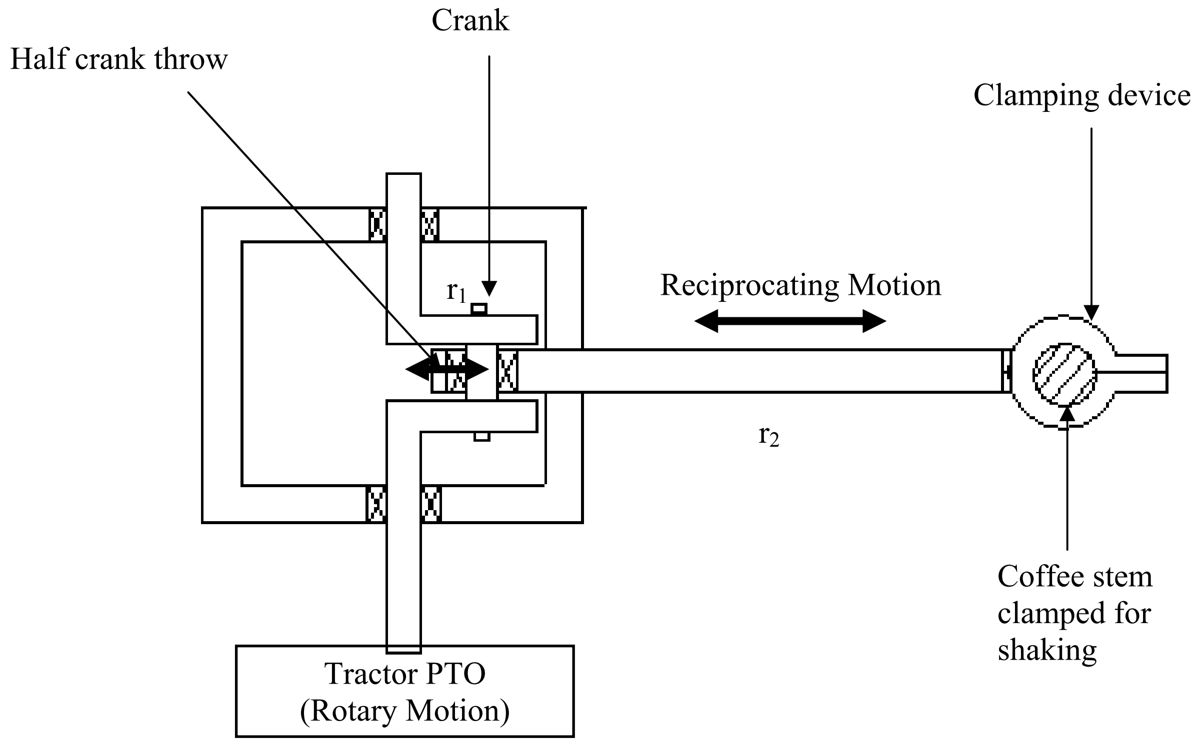

Figure 2. Plan view of the crank slider mechanism used in the experimentation

From the crank slider mechanism shown in Figure 2, the acceleration, *a*, for small values of r_1/r_2 may be estimated as:,

$$a = r_1 \varpi^2 \left(\cos \omega T + \frac{r_1}{2r_2} \cos \phi \omega T \right) \qquad (4)$$

Where:

- T is the period, given by $1/\omega_n$, that is, the reciprocal of Equation 2.
- the phase angle (ϕ) is given by:

$$\phi = \tan^{-1} \frac{c\omega}{k - m\omega^2} \qquad (5)$$

Where

- c is the damping coefficient.

- The stiffness k in Equation (5) equals the weight of the concentrated mass (m) divided by the rod displacement from the rest position.

$$k = \frac{W}{y(t)} \qquad (6)$$

Having obtained an expression of the acceleration, the force applied on a tree by the crank slider mechanism was found by multiplying the acceleration with the mass of the tree.

$$F_0 = ma \qquad (7)$$

Equation (7) gives the force required to shake a single tree. Therefore, to determine the optimum number of trees that can be shaken by a tractor of a given power rating, the available force at the tractor PTO is divided by the force required for a single tree.

The amplitude of the coffee tree vibrating at the natural frequency is obtained from:

$$y(t) = \frac{F_0}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}} \qquad (8)$$

Being the amplitude that would induce the natural frequency, this is also the amplitude at which the highest percentage of coffee harvested was expected during shaking by the crank slider mechanism. The amplitude determined from Equation (8) is then compared to the amplitude from experimental observations at which the highest percentage of coffee was detached. How well the two values compared would give an indication of how efficient it is to model a coffee tree being shaken as a cantilever beam under vibration.

4. MATERIALS AND METHODS

4.1 Determination of Coffee Tree Properties

Experiments were conducted in two coffee plantations consisting of five and nine year old coffee trees at Egerton University, Kenya. The experiments were carried out at the start of the ripening season when it was possible to determine the characteristics of ripe, unripe and dry berries.. Categories of experimental berries were determined on the basis of skin coloration. Ripe berries were considered as those that were yellow, orange and red. Unripe berries were green while dry berries were black or brown.

The bonding strength of the coffee berries was determined by attaching each to a spring balance using a strong adhesive tape. The berry was then pulled from the spring balance and the maximum reading at detachment recorded. A tiny marker pen attached to the scale was used to indicate the end point of the pulling when the berry snapped. This was repeated for 30 ripe berries, 30 unripe berries and 30 dry berries from different trees selected randomly from the two fields used. The mean bonding strength for each experimental category of coffee berries was then calculated.

The mass of 100 berries in each category (viz. ripe, unripe and dry berries) that were randomly sampled from trees in the two fields was measured and the average weight for individual ripe, unripe and dry berries was obtained. The average stem diameter, D, of the coffee trees was obtained from 30 trees using a vernier caliper. The diameter was used to calculate the second moment of area (I) of the coffee trees using Equation (3).

The concentrated mass (m) of trees was determined by weighing five pruned trees and obtaining the average mass. The modulus of elasticity of the coffee tree in bending (E) was determined in accordance with ASTM D198-05a (2005) using pruned coffee stems. It was determined in the wet state in order to be representative of the so as to give a reflection of the actual strength property of the coffee tree stem during shaking.

4.2 Determination of Shaker Parameters

The coffee tree was modeled as a cantilever beam under forced vibration with damping in order to determine optimum operating conditions of a crank slider mechanism as applied to the harvest of *Caffea arabica* such as speed and crank throw and to obtain a method of calculating the optimum number of trees that can be harvested by a prime mover of specific horsepower.

Using the crank slider mechanism, the following parameters were assumed to be affecting the detachment of berries from the coffee tree: the force with which the berries are held onto the trees, the mass of ripe and unripe berries, speed of shaking, duration of shaking, the deflection of the tree during shaking (the crank throw of the crank slider mechanism), height at which the shaker was clamped measured from the ground and the height of the tree. All the trees used for this study were obtained by random sampling of trees in the five year old coffee stand. The selected trees were then pruned to a height of 1.2 m. for uniformity. This was used in Equation (2) as L.

A coffee shaker illustrated in Figure 2 consisting of a variable crank throw (r_1) from 0.01 m to 0.06 m with intervals of 0.01 m was fabricated. The trees were then clamped and shaken at constant PTO speeds of 540 rpm. The position of clamping of the crank mechanism was measured from the bottom of the tree, with variations of 0.4 m, 0.6 m and 0.8 m. The time of shaking was varied at constant speed and was increased from 4 s through 20 s in intervals of 2 s. This was repeated for the following crank throws: 0.02m, 0.03m and 0.04m. This is to mean that a set of three trees was shaken each for a specified amount of time and thereafter another set shaken for a different duration of time and for each duration of time, the percent of ripe berries harvested recorded. This experimental set up is summarized in Table 1.

For each combination of experimental variations outlined in Table 1, the total number of ripe, unripe and dry berries on the tree was counted prior to shaking. Each tree was then exposed to specified vibration characteristics and the detached coffee berries were collected on polythene sheets laid to cover the ground area around each tree. The number and category of detached berries was recorded and the results presented as ratio of ripe berries harvested to initial total of ripe berries counted before harvesting.

Table 1: Summary of the Experimental Setup

Parameter tested	**Range tested**	**Number of replications (trees shaken)**	**Factors held constant**
Crank throw (r_1)	0.01 – 0.06 m	3	• Speed (540 rpm) • Duration of shaking (5 - 15 s) • Position of clamping (0.6 m from the base) • Tree height (1.2 m)
Position of clamping (measured from the base of the tree)	0.4 - 0.8m	3	• Speed (540 rpm) • Duration of shaking (30 s) • Tree height (1.2m) • Crank throw (0.04m)
Duration of Shaking	4 - 20s	3	• Speed (540 rpm) • Position of clamping (0.6 m from the base) • Tree height (1.2 m)

4.3 Model verification

It was necessary to verify whether the field results could be predicted by the model of the coffee tree as a cantilever beam with a concentrated load on one end under forced vibration with damping as presented in Equations (1) through (8). Several field measurements that were useful in verification of the proposed model were determined. These included the modulus of elasticity (E), found to be 17 GN/m^2 for the coffee stems, pruned to a length of 1.2 m and the concentrated mass of the trees was 10 kg. For obtaining the moment of inertia I, the mean stem diameter of 0.03m was used. These values were used in Equations (2) and (3). Hence the natural frequency of the coffee trees in the conditions specified modeled as a cantilever beam with a concentrated mass was found to be 10.82 rad/sec. by Equation (2).

5. RESULTS AND DISCUSSION

5.1 Results from Field Experiments

The variation of percent berries detached at different crank throws was depicted in Figure 3. It was found that the percentage berry detachment increased with tree deflection, and the maximum crank throw coinciding with the maximum berry detachment from the tree was 0.04 m from field experimentation that the tree deflection (crank throw) that yielded the maximum harvest was 0.04 m (Figure 3)

The results of variation in percent of detached berries with different periods of vibration exposure were shown in Figure 4. It is shown that the percentage of berries harvested increased steadily with time of exposure, until 10 s of shaking; the yield was more or less constant. This would imply that resonance occurred at about 10 seconds after the commencement of shaking under the experimental conditions specified. This would explain the steepness of the curve below 10 seconds and the flat profile of the curve in Figure 4 after 10 seconds. The best position of shaking for these particular trees, pruned to 1.2 m was found to be 0.6 m (mid point). Above or below this point yielded fewer berries harvested.

For experiments to determine the optimum height to clamp the crank slider mechanism, it was not possible to obtain results at clamping heights of 0.4 m and 0.8 m respectively, measured from the base of the tree. The only viable height for shaking trees in this plantation was 0.6 m. shaking at 0.4 m resulted in very large deflections on the upper part of the trees that threatened to break them and also seemed to interfere with the rooting system. Shaking at 0.8m was also not fruitful because shaking at that height did not shake branches in the lower sections of the stem and the stem at this point appeared brittle since breakage occurred in the first few seconds of shaking.

It is noted from the recorded results that the maximum percentage of ripe berries obtained in the experiments was not more than 45%. This may appear to be very low compared to those cited in literature review where there were percentages mostly over 80%. The reason for this low percentage is attributable to the fact that the definition for ripe berries in this project was based on colour alone. Ripe berries were classified as those that had become yellow, orange or red. This was because some of the yellow and orange berries were just as easy to detach as the red ones. However, there were some yellow, orange and even red berries that were just as difficult to detach as the green unripe berries. Hence during the shaking, only the berries that were easy to detach fell. All the ones that remained on the tree appeared to be ripe by colour (yellow, orange and red) but were difficult to detach like the unripe berries. Hence this may be considered as a limitation of efficiency rating by mechanical shaker.

An important observation was that all the berries harvested were ripe with just one or two unripe and dry berries per tree. This means that it was possible to obtain a high quality harvest (of exclusively ripe berries), which is responsible for high quality coffee beverage using mechanical shakers.

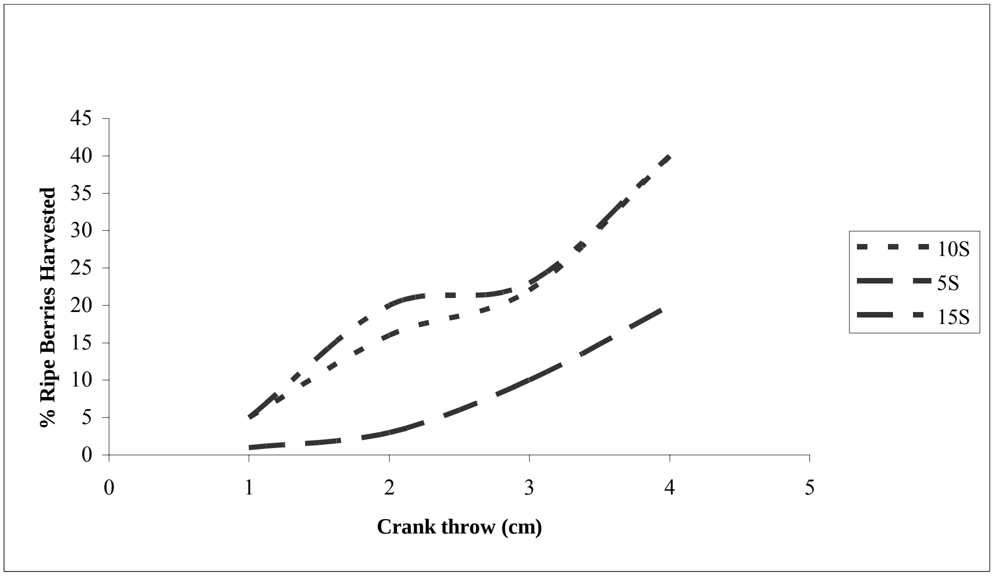

Figure 3. Percentage of berries harvested at different crank throws

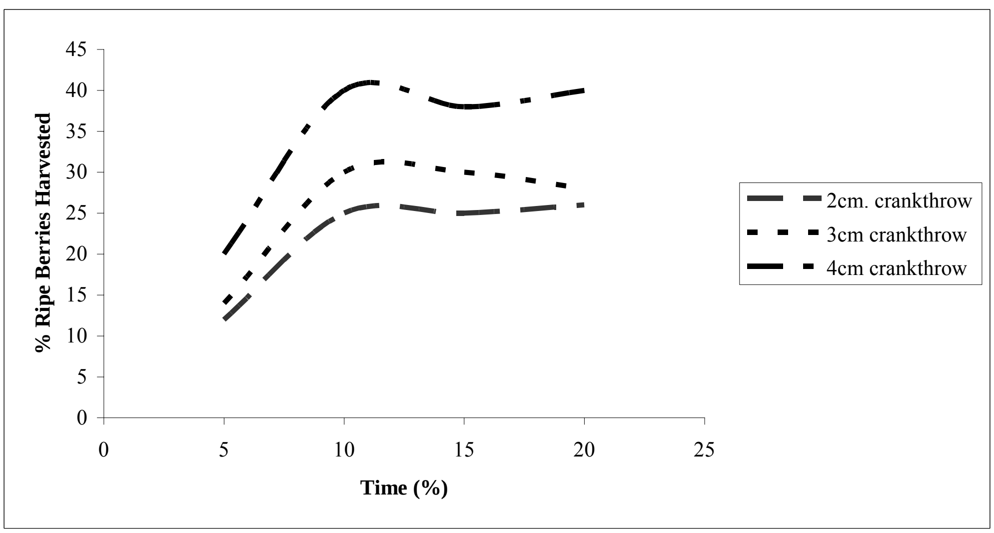

Figure 4. Percentage of berries harvested over time

5.2 Model validation

Using stiffness, *k* value of 1000 N/m calculated from Equation (6) from Park (2003), a damping coefficient of 0.05 Nm estimated from Kashani (2004) the values of the phase angle (ϕ) and the acceleration, *a*, were obtained from Equations (5) and (4) as 0.01 rad. and 1.28 m/s^2 respectively.

Hence the force applied on a 10 kg tree was found from Equation (7) to be 12.8 N from and the amplitude at which the natural frequency or resonance occurred *y(t)* was found to be 0.075 m at the top of the tree by equation (8). This was reduced to a crank throw of 0.038 at the point of shaking. This is very close to the findings from the field experiments that yielded a maximum harvest at a crank throw of 0.04 m

6. CONCLUSIONS AND RECOMMENDATIONS

A verifiable theoretical model that may be used to design a mechanical shaker for harvesting of coffee berries was developed. The optimal model mechanical parameters with which the resulting force of the coffee mechanical shaker would only harvest ripe and dry berries and leave unripe berries to reach maturity were determined. It was concluded that it is possible to find an intermediary force (amplitude and vibration combination) that will remove only ripe berries.

It is recommended that this method of harvesting coffee be further explored for harvesting many trees with a single prime mover. For this research, it was found that a force of 12.8 N is necessary to harvest berries from a single tree. Hence it is theoretically possible to calculate the number of trees that can be harvested from a single power source of known rating. This may be useful in the system shown in Figure 5. However, with so many trees coupled together, it is possible that other forces such as inertia, damping, wind resistance and vibrations in other directions may become more significant than in the case of one tree being shaken. This will be addressed in the coming paper.

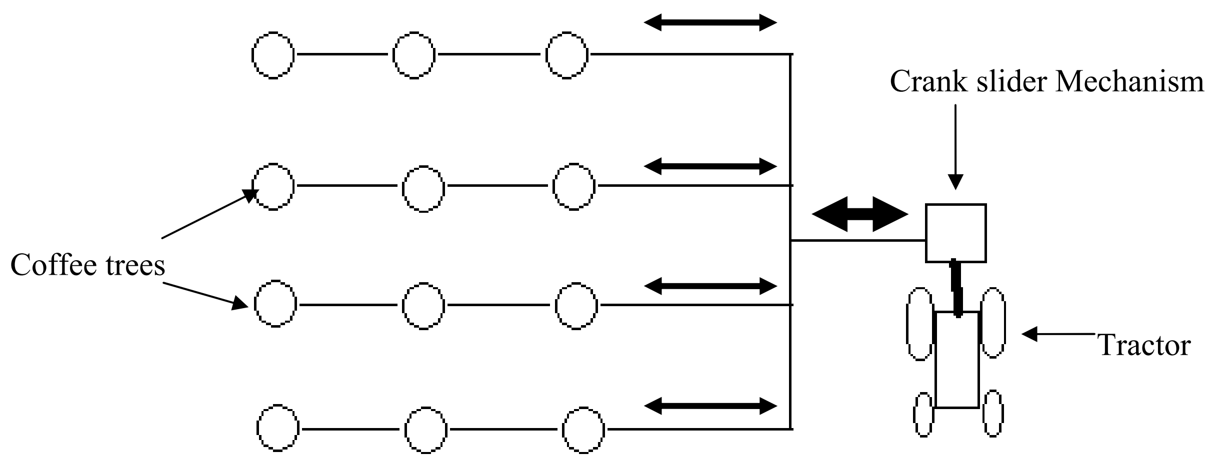

Figure 5: Harvesting several trees from a single power source

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