# Mass and displacement relationships of tree shakers

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***Summary:*** The degree of mechanically harvested fruit removal by shakers is determined by the displacement pattern, the frequency and the amplitude of shaker mechanism attached to the tree trunk. The displacement pattern is derived from the structural setup of the vibration mechanism, the frequency can easily be adjusted by the rev/min (rpm) of the rotating masses. More problems are arising in determining the dynamics of the tree-shaker system. Among others the amplitude of the attachment point and its components, the effective masses reduced to the attachment point.

Recent work gives some new insight into the tree-shaker dynamics including new calculation methods to determine the displacement components and the effective masses reduced to the attachment point. A fully new approach is given to include the vibrating soil mass into the total effective mass. The assumptions are supported and verified by laboratory and field measurements.

## Introduction

Fruit harvesting by manual operations is a very laborious and ineffective activity. Therefore, various innovative ideas and devices were tested and improved to convert the fruit harvesting into a highly mechanized procedure. Already in the 1940's a cable shaker equipped on farm tractors was developed to harvest nuts. In the 1950's different boom shakers and hand-carried shakers were developed and tested, first of all upon trial and error. Therefore, in the early 1960's many researches were undertaken to determine the main relationships among stroke, frequency, fruit removal, duration of shake and other related parameters. Fridley and his co-workers (1960, 1966) have established the fundamental design criteria for different tree shakers. Using Newton's equation of motion, the differential equation of the tree-shaker system was derived and solved. This solution was used for design force, displacement, torque and power requirement.

Recently the vibration characteristics of tree shakers have also been investigated by several researchers (*Canavate* et al. 1980, *Whitney* et al.1990). In these investigations wooden or steel posts were always used as cantilevers embedded in concrete in the ground. This approach provides a convenient reproducible method of testing a shaker, but the conditions used here are very far from the actual field conditions.

Although much effort has been done on the mechanics of tree shakers, several fundamental problems still remain unsolved. The determination of effective point masses acting at the attachment point is one of these fundamental problems. Some researchers gave approximate values for it, but no calculation method has been suggested yet. The attachment height, however, fundamentally influences the effective masses acting on the shaker.

Further problems are arising from the assumption that the restoring force is simply proportional to displacement. Using trunk shakers with low attachment heights, the entire tree vibrates including a given soil mass with the root system together. Since the soil mass has a high damping capacity, the restoring force is much less than the maximum force acting on the trunk. Restoring force can only be originated from pure elastic deformations, therefore the knowledge of displacement components with special regards to the elastic component would be very desirable.

Recent work made an attempt

- to work out a calculation method to determine the effective masses acting at a given attachment height including the soil mass taking part in the vibration,
- to analyse the components of the trunk displacement as a function of attachment heights,
- to determine the elastic component of the total displacement giving the restoring force diminishing the energy requirement.

## Theoretical considerations

The forces acting on a shaker-tree system can be seen in *Figure 1* (slider-crank mechanism). The force $F_g$ generated by the slider crank is passed to the tree trunk. The reacting

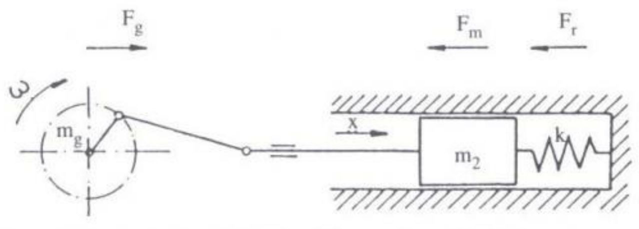


*Figure 1* Mechanical model of the slider-crank mechanism

force $F_r$ on the trunk is given by the total resistance of the tree against the displacement. We assume that this force is proportional to the displacement and an equivalent spring constant, i.e., $F_r = k \cdot x$ .

The equivalent point mass of the tree $m_2$ produces an inertia force $F_m$ acting also horizontally in the same plane. Neglecting the damping effect of the tree, the force balance equation shows the following form

$$F_g = F_r + F_m$$

The slider-crank shaker mechanism, the connecting rod (shaker boom) and the vibrating tree in two different positions is given in *Figure 2*. Using the notations given in *Figure 2*, the equation of motion of the tree-shaker system has the following form:

$$m_g \cdot \ddot{x}_1 = m_2 \cdot \ddot{x}_1 + k \cdot x_2 \qquad (1)$$

where $m_g$ – is the mass of the crank shaker mechanism (housing, crank and hydromotor),

$x_1$ – is the instantaneous displacement of the housing,

$x_2$ – is the instantaneous displacement of the tree,

$m_2$ – is the equivalent point mass of the tree including the shaker boom

k – is the equivalent spring constant of the tree related to the attachment point.

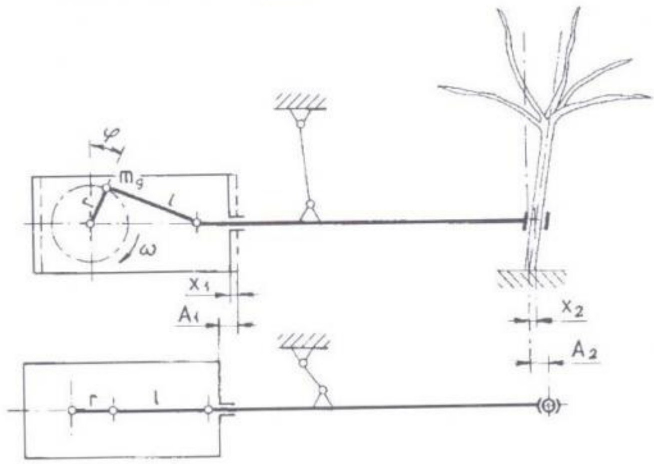


*Figure 2* The tree-shaker model in two different positions

Keeping in mind that $x_1$ is opposit to $x_2$, therefore the following relations are valid:

$$r \cdot \sin\varphi = x_2 - x_1$$

and $$x_1 = x_2 - r \cdot \sin\varphi$$

Using the above relations, Eqn (1) can be brought to the following form

$$(m_2 - m_g) \cdot \ddot{x}_2 + k \cdot x_2 = m_g \cdot r \cdot \omega^2 \sin \omega t \qquad (2)$$

The solution of Eqn (2) gives the maximum forces or displacements in the dead points, at which $\sin w t = 1$ or $-1$, as follows:

$$m_g (r - A)\ \omega^2 = k \cdot A - m_2 A \omega^2 \qquad (3)$$

and the maximum displacement of the tree trunk is

$$A = \frac{m_g (r - A)\ \omega^2}{k - m_2 \omega^2} \qquad (4)$$

or $$A = \frac{m_g r - \omega^2}{k - (m_2 - m_g) \cdot \omega^2} \qquad (4a)$$

Shaker mechanism with two rotating masses have slightly different force equation beacause the mass of the housing is connected directly to the tree, i.e., they are moving together. Therefore in the denominator Eqn (4a) the sum of $m_2$ and $m_g$ must be substituted.

As mentioned above all the researches considered the tree-shaker system as a clamped post suffering elastic deformations only. At the same time our observations have shown that also the root system including a given soil mass performs a significant vibration. Furthermore it is easy to realize that the elastic deformation of the trunk, especially at low attachment heights is far not enough to ensure the prescribed vibration amplitude. As a consequence the trunk must also perform a tilting motion and a pure lateral motion.

The proposed tree model used in this investigation can be seen in *Figure 3*. The total dispacement at the attachment point consists of three components:

$$A = A_1 + A_2 + A_3 \qquad (5)$$

where $A_1$ – is the component of lateral motion,

$A_2$ – is the tilting motion,

$A_3$ – is the elastic deformation.

The elastic deformation can be calculated using the deflection formula for the elastic beam clamped at one end. The total displacement A will be determined by the general relationship of the tree shaker, i.e., by Eqn (4a).

According to Eqn (5), the total spring constant also consists of three components connected in series

$$\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} \qquad (6)$$

The elastic spring constant $k_3$ can easily be calculated, while the other two must be determined experimentally. Because of the highly plastic behavior of soils the spring constants $k_1$ and $k_2$ may be regarded as virtual ones without any restoring effect.

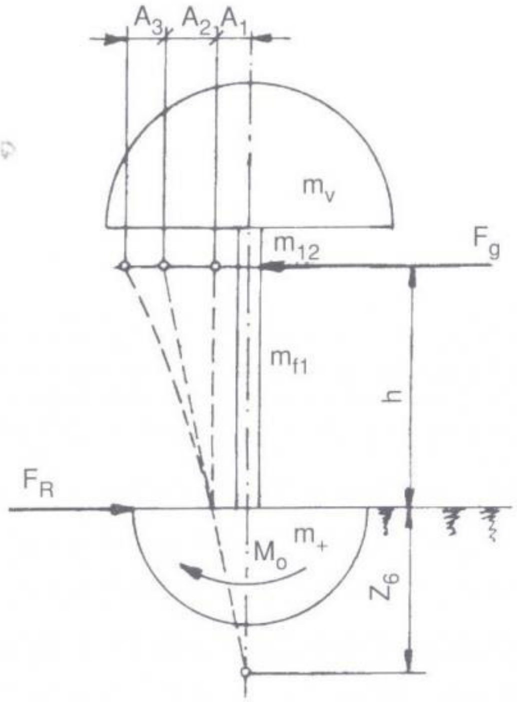

*Figure 3* Displacements of a tree trunk

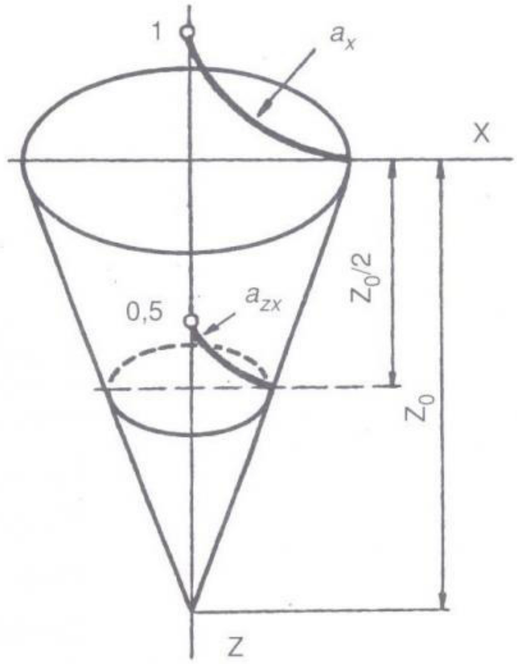

*Figure 4* Supposed distribution of acceleration in the soil body

The total mass $m_2$ taking part in the vibration must be reduced to the attachment point. The resultant reduced mass is putting together from several parts: from the tree trunk, from the limbs and foliage of the tree crown and from the vibrating soil mass including the roots. Using the energy conservation principle the general rule of reducing masses to the attachment point can be written as

$$m_2 = \Sigma\, m_i\, (l_i\, / l)^2 \qquad (7)$$

where $m_i$ – are the actual mass components,

$l_i$ – are the distances between each mass component and the centre of rotation,

$l$ – is the distance of attachment point to the centre of rotation.

The main and entirely new problem is to determine the volume of vibrating soil mass and the distribution of accelerations in it. Our measurements have shown (see in *Figure 6)* that the acceleration on the soil surface has an exponential distribution as a function of distance measured from the tree trunk. Therefore we use the following approximation

$$a_x = B \cdot e^{-bx} \qquad (8)$$

where the constants B and b will be given from the experimentally obtained curves.

We need also the distribution of accelerations in the soil body as a function of depth. This relationship is today not known exactly, but the form and depth of the root system give some basis. As a first approximation a cone shape with the characteristic depth $z_0$ was taken *(Figure 4)* and Eqn (8) will be modified to

$$a_{zx} = B\,\frac{z_0 - z}{z_0}\, e^{-bx} \qquad (8a)$$

Constant b also varies with depth and the following approximation was chosen:

$$b = b_0\,\frac{z_0}{z_0 - z}$$

If $z = 0$, than on the surface $b = b_0$ holds.

Using the experimentally obtained distribution of acceleration an equivalent soil volume related to the unit acceleration can be calculated

$$V_s = 2\pi \int_0^{\infty}\int_0^{z_0} x\left(\frac{z_0 - z}{z_0}\right) e^{-b_0 \frac{z_0}{z_0 - z} x}\, dx\, dz$$

This volume multiplied by the soil volume density gives the equivalent soil mass taking part in the vibration and acting in the centre of gravity of the cone. Using Eqn (7), this mass can be reduced to the soil surface and in this case we can write

$$V_{ss} = 2\pi \int_0^{\infty}\int_0^{z_0} x\left(\frac{z_0 - z}{z_0}\right)^3 e^{-b_0 \frac{z_0}{z_0 - z} x}\, dx\, dz$$

and its solution is

$$V_{ss} = \frac{z_0 \pi}{3 b_0^2} \qquad (9)$$

The soil mass reduced to the soil surface is given now by multiplying the volume with the soil density

$$m_s = \rho_s \frac{z_0 \pi}{3 b_0^2} \qquad (10)$$

where $r_s$ – is the soil volume density (w.b.).

## Material and method

Three different inertia-type tree shakers were used and investigated. A more detailed investigation was undertaken on a tree shaker with slider-crank mechanism allowed the use of several attachment heights between 0.3 and 1.1 m. The counter rotated unbalanced weight system has a reciprocating action in one direction, while the third assembly had a circular translation action by rotating weights at different speed. The assembly weights supplying the exciting force were also different: 135, 770 and 547 kg respectively.

The accelerations on the soil surface and on the tree trunks were measured using two-component acceleration transducers. Measurements were made in the direction of row and perpendicular to that. Accelerations were always measured at the attachment point and simultaneously on limbs at different heights. Latter was needed to evaluate proper corrections for determining the reduced mass of the tree crown.

Tests were conducted in several prune orchards of the same species (Beszterce) having different ages between 10–15 years and, as a consequence different trunk diameters between 130–250 mm. The total duration of each test was 6–10 seconds.

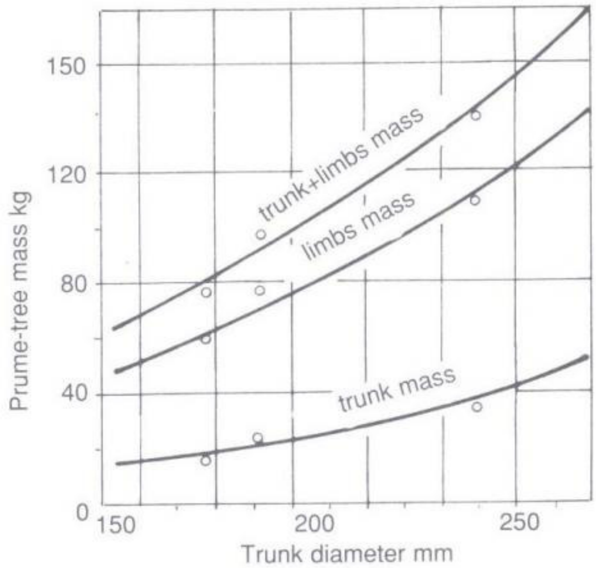


*Figure 5* Trunk and limb masses versus trunk diameter

Special measurements were carried out to determine the acceleration distribution in the soil body around the tree trunk. Acceleration transducers were mounted on steel plates driving into the soil to a depth of 15 cm. Measurement units were placed in the immediate vicinity of the trunk as well as in distances of 0.5, 1.0, 2.0 and 3.0 m.

In order to calculate the mass components the average weight of the trunk and limbs was also measured as a function of trunk diameter. This relationship is shown in *Figure 5*.

## Results and discussion

As outlined above, a given soil mass and the root system play also an important role in the determination of effective masses reduced to the attachment point. Therefore the acceleration field around the tree trunk was measured and results for the three different shakers are demonstrated in *Figure 6*. The different tree shakers exert near the same action on the soil body differing only in its amplitude. Constant $b_o$ in Eqn (8) and (10) can be determined from the distribution curves, which has values of 1.32, 1.52 and 1.51 $m^{-1}$ respectively.

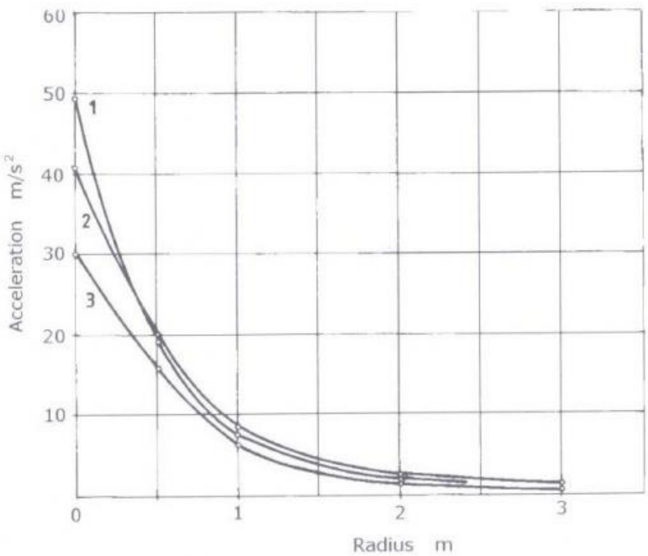


*Figure 6* Distribution of accelerations in the soil body, for there different shakers

The characteristic depth $z_o$ depends on age and species of fruit trees. For 10–15 year-old prune trees 90% of the roots are located above the 60 cm depth level, therefore, generally $z_o$ = 60-65 cm was taken.

Using the vibrating soil mass we have calculated the equivalent point mass reduced to different attachment heights. These results are demonstrated in *Figure 7*. It is interesting to note that the soil mass dominates at lower attachment points. As the attachment height is increasing the equivalent mass is decreasing and the portion of the soil mass strongly decreases.

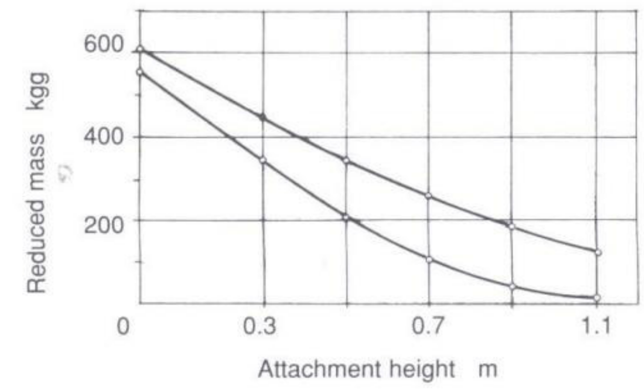


*Figure 7* Reduced mass versus attachment height. 180 mm dia

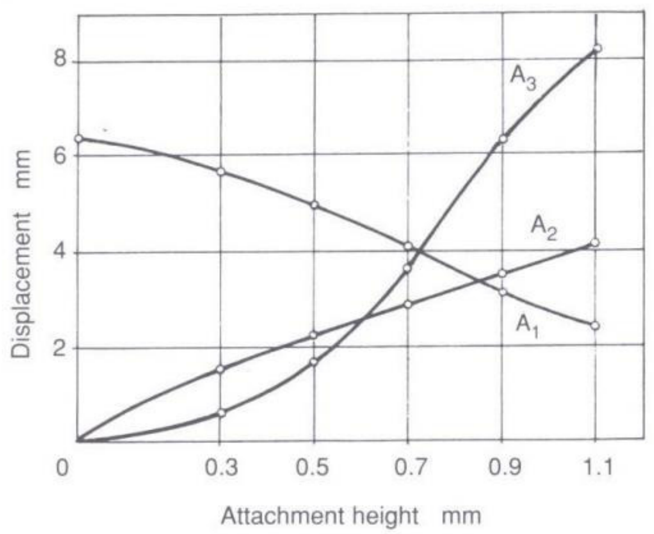


*Figure 8* Displacement components as a function of attachment height

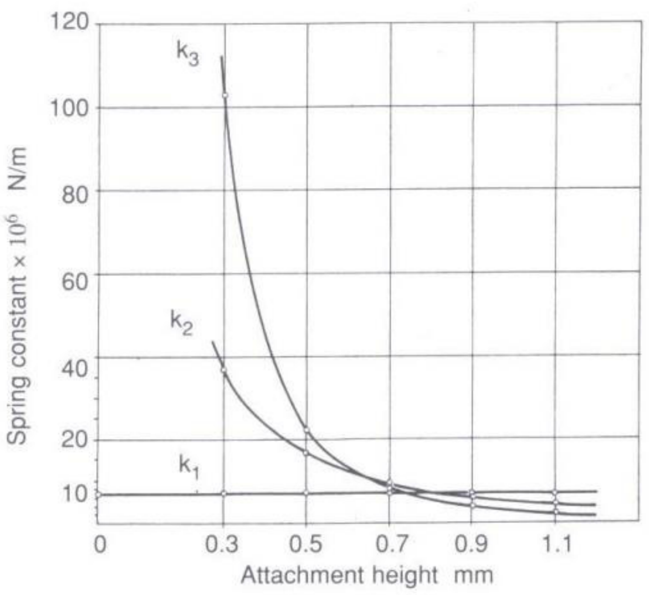


*Figure 9* Spring constants versus attachment height

In the course of our experiments the accelerations of trunk as a function of trunk diameter and attachment height was determined. In the possession of acceleration the total displacements were also calculated. The components of the total displacement can also be calculated, if the $k_1$ and $k_2$ spring constants are known. The $k_1$ spring constant is related to the pure lateral motion, therefore its value can be calculated at zero attachment height. Having the total displacements for different attachment heights its value for zero attachment height may be extrapolated. Doing so, we have obtained the value of $k_1$, which is valid for each attachment height.

The components of the total displacement as a function of attachment height can be seen in *Figure 8*. At low attachment heights the parallel motion dominates and the elastic deformation of the tree trunk is very little. This means that in this case also the portion of elastic restoring force in comparison to the total force is low. With increasing heights the elastic deformation of the trunk gradually increases.

The variation of spring constants are demonstrated in *Figure 9*. The spring constant $k_1$ is unchanged, while the other two are dependent on the attachment height.

## Conclusions

Based on theoretical and experimental investigations, the main conclusions are the following:

- a more realistic tree-shaker model was developed and the resistance coefficients were determined experimentally,
- the new model allows to determine the components of the total displacement, which are highly dependent on the attachment height,
- a new calculation method was introduced to determine the equivalent point mass reduced to the attachment height. At low attachment heights the major part of the point mass is given by the vibrating soil mass,
- due to the high damping capacity of soils, the restoring force is generally much less than the total force acting on the tree.

## References

**Canavate et al. (1980):** Design and testing of a tree shaker.ASAE Paper No. 80–1045, St. Joseph, MI: ASAE.

**Fridley, R. B. & Adrian, P. A. (1960):** Some Aspects of Vibratory Fruit Harvesting . Agricultural Engineering 41(1): 28–31.

**Fridley, R. B. & Adrian, P. A. (1966):** Mechanical harvesting equipment for deciduous tree fruits. California Agricultural Experiment St. Bulletin 825.

**Whitney, J. D. et al. (1990):** Dynamic analysis of a trunk shaker-post system . Trans. ASAE 33 (4): July–august.