



## A NEW SHAKER HEAD DESIGN FOR REDUCING BARK INJURIES ON FRUIT TREES

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### Abstract

To reduce bark damaging moments on the fruit tree trunk, a new shaker head arrangement is proposed. By applying two identical complete shaker units symmetrically on both sides of the trunk, the resulting shaking force will be normal to it and uniform in any direction. To prove the assumption, a theoretical model was set up and a laboratory model was built and tested. The theoretical model made the calculation of pure centrifugal forces of the eccentric shaker masses possible. Besides the new shaker head arrangement, the laboratory model enabled the study of the performance of present shaker heads. Test results lived up to the expectations: In case of the new shaker arrangement, the acceleration pattern was nearly uniform in all directions, both in the free and “tree” shake mode. In case of the usual shaker arrangements, asymmetric acceleration distributions were measured, which, besides injuring the bark, may result in lower fruit detachment rate.

### Keywords

fruit harvest; inertial shaker; shaker head; bark injury

### 1. Introduction

In the mechanical stone fruit harvesting practice, both uni- and multidirectional inertial shaker machines are used. The unidirectional shakers cause theoretically only normal force to the trunk. In the praxis however there are other effects, which may damage the bark. Maximum displacements were found by Affeld et al. [1] to be 2,5 times greater during start-up and shut-down, than at steady-state. Relative displacements between the shaker and the trunk were also excessive and can exceed tolerable bark strength limits.

According earlier experiments the effect of shaking direction influences the detachment rate [2]. By shaking the trees in multiple directions, nearly uniform acceleration acts on fruits in all directions. This results in higher detachment rate, compared to the uni-directional shaking. The phenomenon was also modelled and proved by FEM [3] [4].

Multidirectional shakers produce forces not only in normal, but in tangential directions. The tangential forces tend to separate the bark from the cambium layer, which can cause long-lasting damage to the tree. In practice in order to reduce bark injuries, lubrication is applied between the sling surfaces of the shaker head [5] [6].

In all cases, the shaker head is clamped to the trunk and is free to move, relative to the frame of the carrier machine. The present multidirectional shakers use a pair of counter-rotating eccentric masses to generate centrifugal forces changing in value and direction. The freedom of moving relative to the carrier is assured by the suspension of shaker head via 3 rubber isolators or chains (Figure 1).

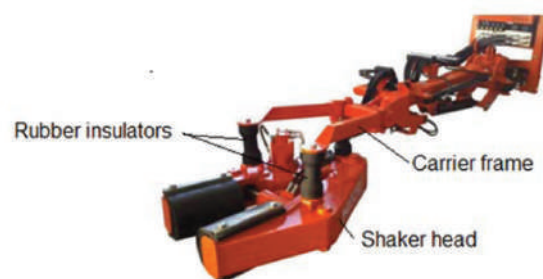


Figure 1. Tractor-mounted tree shaker by the company Agricola Noli, S.A.

One possible arrangement of eccentric rotating masses in the shaker head is stacking, where those are

rotating around the same axle. The dynamics of such shakers was studied by Snell and Birrell [7]. According to their findings beside normal forces, tri-axial torsion moments are raised on the tree trunk, which may damage the bark (Figure 2).

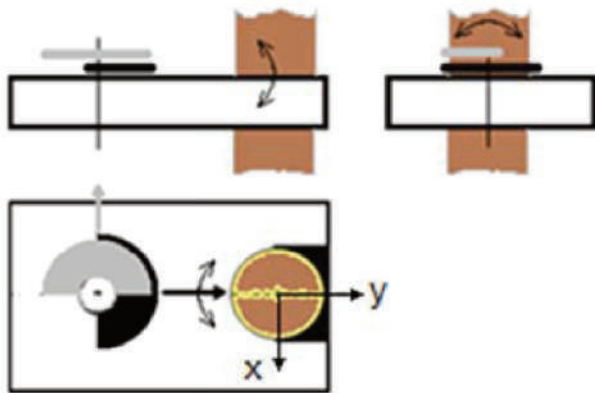


Figure 2. Typical stacked eccentric mass counter rotating system as it awakes tri-axial torsion moments on the trunk

In practice two other arrangements are also used as Figure 3 shows. To the left the eccentric masses are symmetrically placed on both sides, to the right on one side of the trunk. In both cases the energy-wheels rotate in the same plain, their centres of rotation and the centre line of the shaker head clamps are in line. Thanks to these designs two of those harming moments are excluded. The only remaining one is still harmful as it tends to turn off the bark of the trunk in the plane of the wheels (Figure 3).

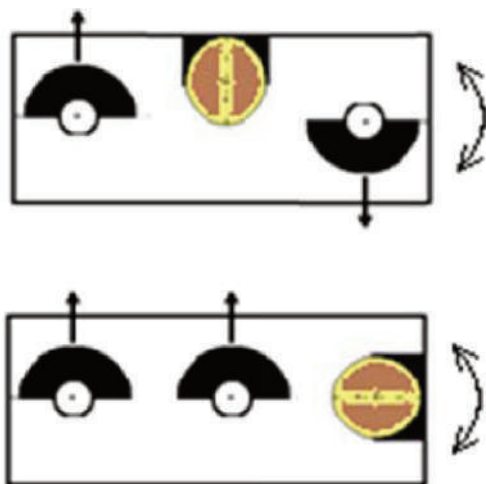


Figure 3. Shaker head with two rotating eccentric masses placed on both sides of the trunk and on one side in line with the tree trunk

Theoretically, by choosing different angular velocities and eccentric masses for the rotating

eccentric masses, a large scale of shaking forces or acceleration patterns can be achieved [8]. Horváth [9] studied and compared the shaking patterns in x-y plane of two uni- and one multidirectional shaker. As expected, the acceleration pattern of the unidirectional shakers was a narrow stripe, while the multidirectional shaker, working according to Figure 3 on the left, has shown a multidirectional pattern in tree shaking. Abdel-Fattah et al. [10] evaluated the shaking patterns of 21 commercial multidirectional shaker machines in x,y and z directions. They found that the displacement in the x and y direction differed significantly in all cases: on average 9.3 versus 4.4 mm respectively. The direction x is explained in Figure 2.

To avoid the third moment (Figure 3) the shaking force should act normally to the trunk axis in any shaking directions. Presuming vertical trunk position and symmetrical limb distribution, the shaking pattern would be symmetric and would not harm the bark of the tree in this case. Fodor [11] studied many technical solutions, which could fulfil these requirements. His final design enabled a pulsating force to rotate along curved rails around the centre of the trunk during shaking. Force pulsation was generated by two counter rotating eccentric masses. Unfortunately the construction would be complicated compared to the present shaking heads. There is no report of its realisation and field testing.

## 2. Materials and Methods

In this paper a new construction model is presented, which is able to fulfil the requirements of non-damaging shaking by a simple method. The principle of the idea is explained in Figure 3. If two identical and parallel forces  $F/2$  are acting on a symmetrical body as shown in Figure 4, their effect is summed up in the midpoint, independent of the direction of forces, without causing any moment around it. Let's now place the tree trunk in the midpoint.

Following from the above, two identical and synchronised shaking unit can generate a force pulsating and changing directions on the tree trunk without generating harmful moments.

In order to prove the idea, a small laboratory model was designed and constructed. The arrangement of the model is shown in Figure 5. The shaking unit included a pair of two synchronised counter-rotating eccentric masses, the catching part and the drive.

The eccentric masses were of different size and had the form of half rings. This way they were able to rotate in the same plane without resulting in undesired moments. The rings were driven by chains from an external point by an electric drilling machine through

a flexible axe. This arrangement made possible the clamping of trunks with different diameters. As Figure 4 shows, the internal and external rings were rotating in opposite directions and at different speeds. The shaking unit was suspended from an external frame by tree cables (see in Figure 4 to the right). These made possible for the shaker to move independently from the frame. The tree trunk was

replaced by a polyethylene tube of 25 mm external diameter in “tree” shaking mode.

When applied, the lower part of the plastic tube was strongly fixed to bottom of the external frame, the upper part to the shaking head. That’s why the acceleration of the tube at its fixing point to the shaker was regarded to the same as of the shaker itself.

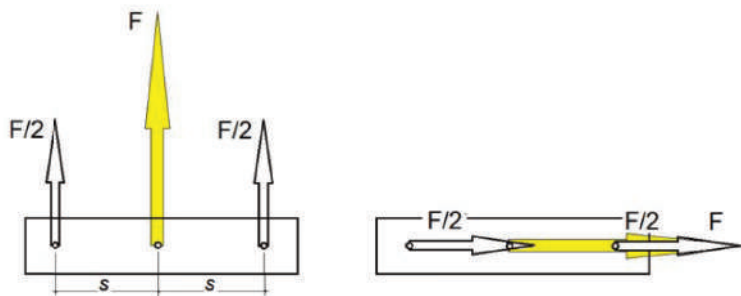


Figure 4. Two parallel and identical shaking forces don't result turning moment

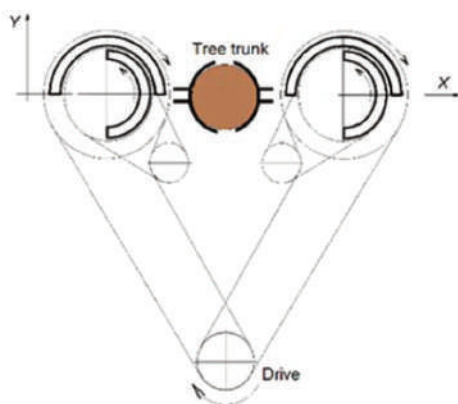


Figure 5. The design of the model and its realization (on the photo one of the diving chains is removed)

Figure 6 shows the dynamic model for both sides of the shaker head. The equations (1-4) of centrifugal forces for each side (according to Figure 5) are:

$$F_x = F_1 \cdot \cos \varphi_1 + F_2 \cdot \cos \varphi_2 \quad (1)$$

$$F_y = F_1 \cdot \sin \varphi_1 + F_2 \cdot \sin \varphi_2 \quad (2)$$

where

$$F_1 = m_1 \cdot s_1 \cdot \omega_1^2 \quad (3)$$

$$F_2 = m_2 \cdot s_2 \cdot \omega_2^2 \quad (4)$$

The values  $s_1$  and  $s_2$  are the distances between the centre of rotation and the centre of gravity of the half rings,  $m_1$  and  $m_2$  are the masses of rotating rings,  $\omega_1$  and  $\omega_2$  are their angular velocities.

The equations (5-6) for those distances are

$$S_1 = \frac{2 (R_e^3 - R_i^3) \sin \alpha_1}{3 (R_e^2 - R_i^2) \alpha_1} \quad (5)$$

and

$$S_2 = \frac{2 (r_e^3 - r_i^3) \sin \alpha_2}{3 (r_e^2 - r_i^2) \alpha_2} \quad (6)$$

where the indexes i and e mean internal and external,  $\alpha_1$  and  $\alpha_2$  are the half central angles of the rings (see Figure 6 in right) In this case  $\alpha_1 = \alpha_2 = 90^\circ$

Ortiz-Canavate [8] declared that the shaking pattern of a double-eccentric-mass shaker depends on the ratios  $m_1 \cdot s_1 / m_2 \cdot s_2$  and  $\omega_1 / \omega_2$ .

On the model design the aim was to achieve a star shape shaking pattern. With the appropriate choice of

eccentric masses and geometrical sizes, the ratio for  $m_1 \cdot s_1 / m_2 \cdot s_2$  resulted in 0.46, for  $\omega_1 / \omega_2 = 1.22$  ( $R_e =$

3.7 cm,  $R_i = 3.2$  cm,  $r_e = 2.8$  cm,  $r_i = 2.1$  cm,  $s_1 = 1.6$  cm,  $s_2 = 2.2$  cm,  $m_1 = 0.07$  kg,  $m_2 = 0.108$  kg.)

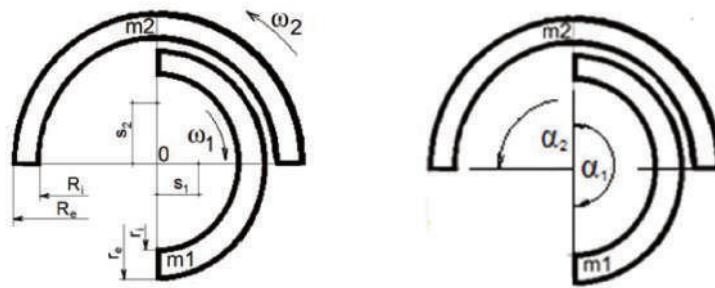


Figure 6. Geometry of the rotating rings

The shaking pattern for the system with  $\omega_1=90$  1/s,  $\omega_2=73,8$  1/s,  $s_1 = 1.6$  cm,  $s_2 = 2.2$  cm, and doubled  $m_1$  and  $m_2$  (due to the two shaker units) is shown in Figure 7. This pattern however is valid for a system composed of a pair of rotating masses. It doesn't include either the frame of the shaker and its drive or the effect of shaken tree.

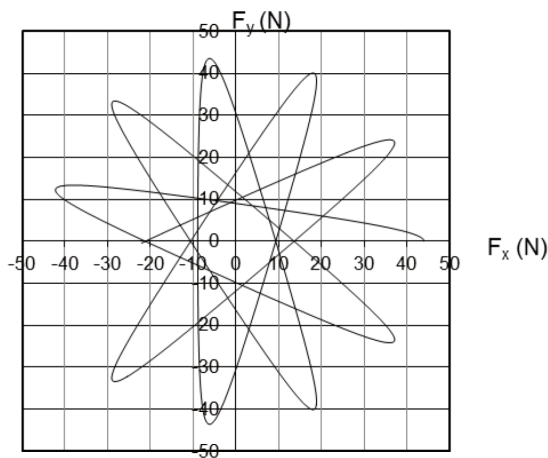


Figure 7. Calculated shaking force pattern with the data of two shaking units

To study the new and the conventional shaker head's behaviour laboratory tests were carried out in the following arrangements:

- 2.1 Both shaking units are driven, free shaking
- 2.2 Both shaking units are driven, "tree" shaking (left in Figure 5).
- 2.3 One shaking unit is driven only, free shaking
- 2.4 One shaking unit is driven only, "tree" shaking (right in Figure 5).
- 2.5 The rings are coupled on both side ( $m_1 + m_2 = 0,178$  kg) and driven  $\omega_1 / \omega_2 = -1.22$ , free shaking
- 2.6 The rings are coupled on both side ( $m_1 + m_2 = 0,178$  kg) and driven  $\omega_1 / \omega_2 = -1.22$ , "tree" shaking
- 2.7 The rings are coupled on both side ( $m_1 + m_2 = 0,178$  kg) and driven  $\omega_1 / \omega_2 = -1$ , "tree" shaking

Accelerations in x-y-z direction were measured and registered by an accelerometer built in a mobile phone with the following specifications: Name: BMA254, vendor: Bosch Sensortec, version 1. Resolution: 0.019153614. Max. range: 39.2266. Power: 0.13 mW.

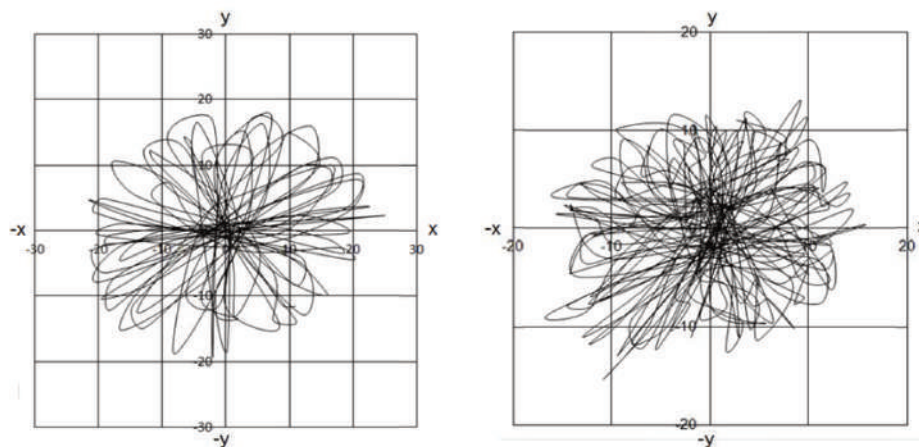


Figure 8. Accelerations measured in free (to the left) and in "tree" shaking arrangement of the model



The mobile phone was fixed to the shaking frame as Figure 8 shows. Fixing was made by placing the phone in an aluminium plate with flanges and framed by a thin robber stripe. It was presumed, that this way the natural frequency of the plate-phone system resulted in higher natural frequency than the applied shaking frequency. This latter was kept in the range of 14-18 Hz during all tests.

- 2.1 Both shaking units are driven, free shaking
- 2.2 Both shaking units are driven, "tree" shaking

To the left in Figure 8 the acceleration diagram of the proposed new shaker head arrangement is

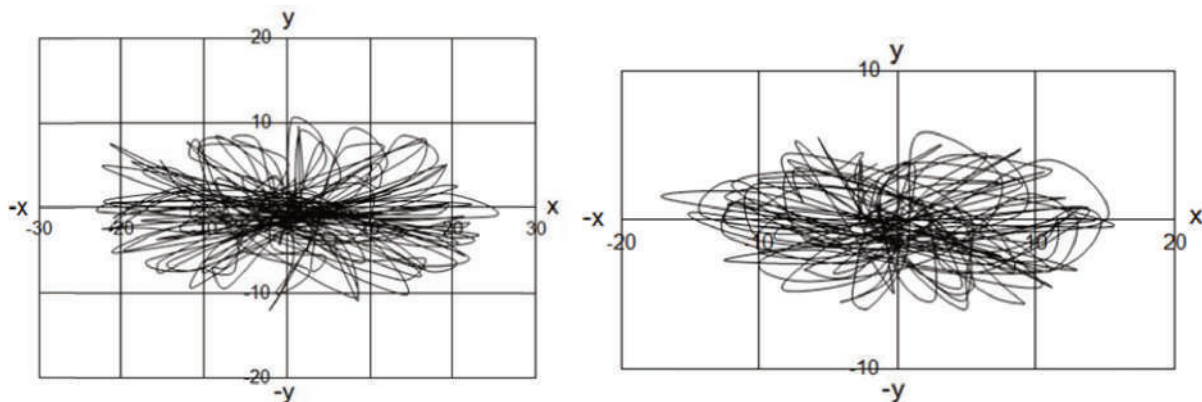


Figure 9. Acceleration pattern when shaking with one counter rotating system.  
To the left: free shaking, to the right: "tree" shaking

- 2.5 The rings are coupled on both side ( $m_1 + m_2 = 0,178 \text{ kg}$ ) and driven  $\omega_1 / \omega_2 = -1.22$ , free shaking
- 2.6 The rings are coupled on both side ( $m_1 + m_2 = 0,178 \text{ kg}$ ) and driven  $\omega_1 / \omega_2 = -1.22$ , "tree" shaking

This arrangement imitates the shaker in Figure 3 to the left. The eccentric rings on both side of the model

were coupled so that the internal and external ones overlapped each other. This way the rotating eccentric masses in both side resulted in 0,178 kg. Their speed ratio was  $\omega_1 / \omega_2 = -1.22$ . Tests were carried out in free and "tree" shaking mode. The acceleration patterns were similar to that what Horváth [9] has experienced (Figure 10).

presented at free shaking (without the plastic tube). To the right in Figure 8 the same shaker was connected to the plastic tube („tree" shaking).  
2.3 One shaking unit is driven only, free shaking  
2.4 One shaking unit is driven only, "tree" shaking

Figure 9 shows the acceleration patterns when one of the driving chains was removed. The photo in Figure 5 shows this setup: it complies with the stacked eccentric mass counter rotating system without its first two undesired moments (Figure 2). To the left, the pattern for free shaking is presented, to the right, "tree" shaking.

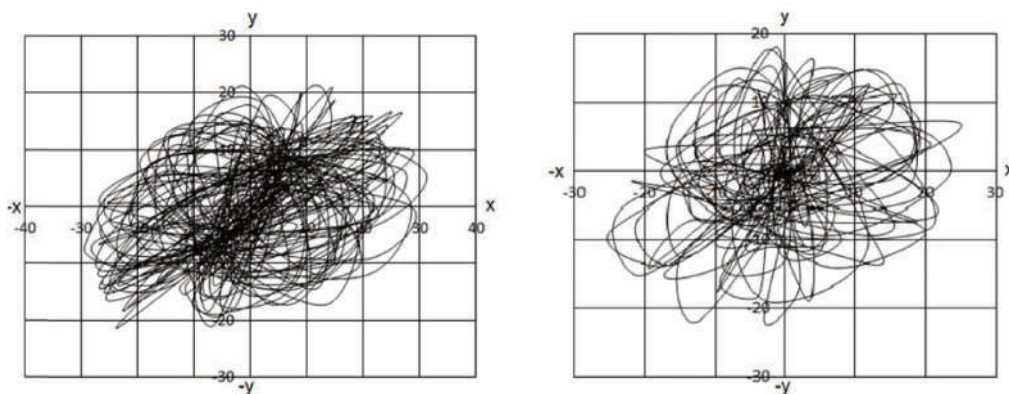
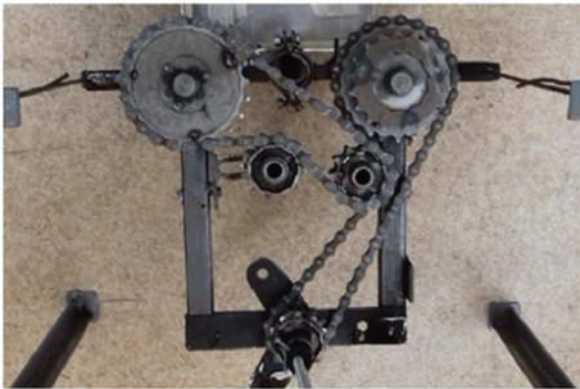


Figure 10. Acceleration pattern, when shaking with two counter rotating and uniform size eccentric masses. To the left: free shaking, to the right: "tree" shaking

2.7 Single eccentric mass is driven on both sides with  $m_1 = m_2$ , “tree” shaking

The setup on Figure 11 imitates the one-directional shakers with a pair of counter-rotating uniform size



masses [7] [9]. In the model the rings on both side are coupled, so  $m_1 = m_2 = 0.178$  kg, the speed ratio:  $= -1$ .

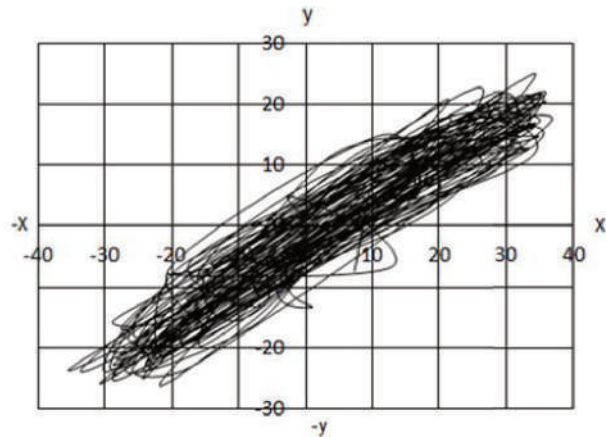


Figure 11. The setup when one eccentric mass is driven on each side with  $m_1 = m_2$

Acceleration patten for one-directional shakers should be theoretically one single line both in free and “tree” shaking. Figure 11 shows instead a stripe of lines. This may be the consequence of inaccuracy in the mechanical system. The tilt angle of the stripe is the angle of the two rotating eccentric masses when in uniform position.

### 3. Results and Discussion

As expected, in the proposed arrangement the two identical and synchronised units worked in harmony: the resulting shaking pattern was nearly symmetric in both the free and “tree” shaking mode. The slight asymmetry can be explained by the asymmetric mass-distribution of the shaker head: as mentioned earlier, the new shaker arrangement works perfectly only when the shaking unit is symmetrical both in x, y and z direction (Figure 4).

Figures 10 and 11 coincide well with the test results of Horváth [9] as well as of Abdel-Fattah [10]. Concerning the direction of asymmetry in shaking patterns, in contrast to the shape in Figure 9, Abdel-Fattah et al. [10] measured larger accelerations in direction y than in x. This may be in conjunction with the different suspension geometries and centre of gravity positions of the model and real shaker machines.

Comparing the model results of the shakers in Figure 2 and left in Figure 3, the latter produced more equalised acceleration pattern (see Figures 9 and 10). However its torsion moment around the axis z is still harmful for the bark.

The advantage of the new shaker head arrangement is proven by the comparison of Figures 8, 9 and 10 both in free and “tree” shaking. The new concept enables the symmetric shaking of trees in any directions.

The model was also able to present the typical shaking pattern of one-directional shakers. The test results can be applied to the estimation of inertial masses in the model. The maximal calculated centrifugal force is  $F_c = 44$  N (in Figure 7), which is generated by the two sets of shaker units. In case of the model, the maximal acceleration  $a_{max}$  at free shaking was measured to be approximately  $20 \text{ ms}^{-2}$  (Figure 8). According to Newton’s law (Equation 7) the inertia force:

$$F_i = m_t \cdot a_{max} \quad (7)$$

whereas  $m_t$  is the total mass of the shaker unit,  $a_{max}$  is its maximal acceleration. The inertia force is generated by the centrifugal force, hence Following from this, in free shaking the total mass, including the frame (Equation 8), drive and the eccentric masses is

$$m_t = F_c / a_{max} = 2,2 \text{ kg.} \quad (8)$$

The weighing of the shaking unit has led to similar result:  $m_{t\text{measured}} = 2,13$  kg, which is near to the calculated value. By accomplishing the same calculation for the “tree” shaking mode, where  $a_{max} = 13 \text{ ms}^{-2}$ , the total mass, including now the “tree” as well resulted  $m_{tt} = 3,38$  kg. In this case the

“tree” load in the system is the difference between  $m_{tt}$  and  $3,38-2,2=1,18$  kg.

#### 4. Conclusion

The presently used three different shaker head arrangements cause harmful moments to the tree trunk, which are eliminated on the most sophisticated products by lubrication between clamping head layers. The shaking pattern of the three type units is more or less asymmetric, which is disadvantageous from the point of view of fruit detachment. The new shaker concept, presented in this paper as a laboratory model, excludes all of those moments and generates a symmetric acceleration pattern. The shaking force is generated here by a pair of two synchronised counter-rotating eccentric masses which result in uniform size acceleration in any direction. The eccentric masses in the model are of half-ring shape, rotating around the same axle. This arrangement excludes all the disadvantages of stacked eccentric mass units by not generating any harmful moments.

The two pair of rotating eccentric masses could be replaced by two linear pulsators, turning around their own vertical axis. Calculations with the model data coincided well with the laboratory test results, which prove the conformity of the model for designing full-sized shaking machines. The calculated and measured total mass of the shaker system coincided well, which is another prove of the right modelling. Further research is planned to detect the reason of asymmetry in shaking patterns of conventional harvester machines.

#### Acknowledgement

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