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Indicators of a fruit detacher with non-symmetric angular oscillations at removing tomato fruits

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Abstract

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The main qualitative and quantitative indicators of a newly developed fruit detacher with non-symmetric angular oscillations have been investigated at inertial removal of fruits of table tomato varieties from stems. The detacher removes over 95% of the fruits of examined tomato varieties 'Tomsk' and 'Tobray', without damaging them mechanically at frequency of oscillations from 10.8 to 13.3 Hz and initial elastic moment of the clutch from 0 to 2.0 Nm. The detacher achieves the productivity for plants from 1.554 to 11.650 $kg \cdot s^{-1}$ and the productivity for fruits of 0.827 to 6.921 $kg \cdot s^{-1}$ for each meter of its working width. The best qualitative indicators were observed at the productivity range from 2.460 to 4.621 $kg \cdot s^{-1}$. During operation, the device allows smooth adjustment of both number of impacts and speed of moving plants towards the exit, which distinguishes it from existing shaker drums. The developed fruit detacher can be integrated into tomato harvesters and to be tested for inertial removal of the fruits of other crops.

Keywords: tomatoes; fruit detacher; mechanization

Tomatoes are among the most popular vegetables with 160–171 million tonnes annual production in the world for the period 2012–2014 (www.fao.org/faostat/en/). Harvesting of tomato fruits consumes over 50% of the total cost for their cultivation. The mechanization of this technological operation reduces labour costs up to 10 times therefore many devices have been developed for this purpose. They achieve requirements for harvesting tomatoes for processing, but their efficiency is not sufficient at harvest of table varieties. The removal of fruits from plants determines the main indicators of machines for harvesting tomatoes. This operation is performed by several devices based on inertial principle. The most widely used are shaker conveyor and shaker drum (Mortev et al. 2013).

The shaker conveyor has large mass and sizes. It gives stems vibrations with a frequency of 4 Hz and amplitude of 0.05 to 0.1 m. Moving stems is at low speed, which limits the productivity of the entire harvesting machine. Moreover, this device gets out of order very often because of reversal loads in supporting chains.

The shaker drum is arranged transversely over the conveyor that supports stems with attached fruits. In operation, the drum fingers penetrate between stems and impart angular vibrations for detaching fruits. After that, they fall onto a collecting belt, below the conveyor (Fitzmaurice et al. 1982).

Angular vibrations are generated by a pulse generator of Chalmers (Lester 2009). In principle, the vibrations have equal angular amplitudes in both directions of rotation of the drum. In practice, the equality of amplitudes is distorted by the forces of friction and air resistance in the generator. The difference between amplitudes is unsustainable, therefore, existing shaker drums are used for imparting vibrations to stems only, but for their moving different types of conveyors are applied. Another disadvantage of shaker drums is the lack of opportunity to adjust angular amplitudes in both directions of rotation as well as the ratio between

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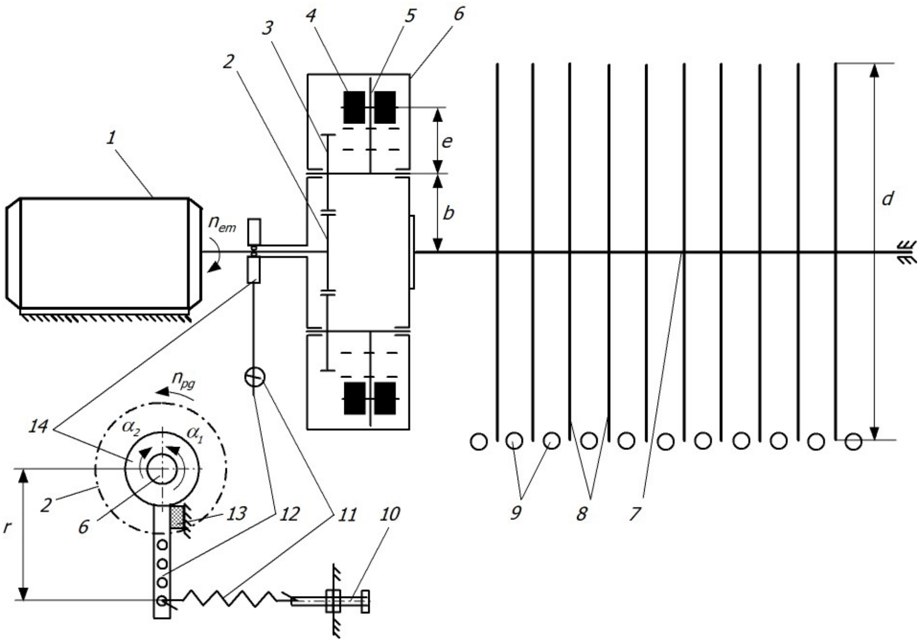

Fig. 1. Scheme of the fruit detacher with non-symmetric angular oscillations
1 – electric motor, 2 – central gear, 3 – planet gear, 4 – eccentrically located weights, 5 – arm, 6 – carrier, 7 – shaft, 8 – fingers, 9 – grate, 10 – tensioning screw, 11 – spring, 12 – lever, 13 – buffer, 14 – one–way roller clutch; n_{em} – rotational frequency of the electric motor; n_{pg} – rotational frequency of the-one way clutch; α_1 – counter-clockwise angular amplitude; α_2 – clockwise angular amplitude; *e* –eccentricity of the mass; *b* – displacement of the axis of rotation; *d* – diameter of the shaker drum

them regardless of vibrations frequency (Didenco et al. 1994).

At the Agricultural University – Plovdiv, Bulgaria a fruit detacher with non-symmetric angular oscillations was developed and patented. It moves stems toward exit of the device and simultaneously inertially detaches fruits from stems of table tomato variety without their mechanical damage (Ishpekov et al. 2015).

The aim of the study is to determine the main qualitative and quantitative indicators of the developed fruit detacher at removing fruits from stems of table tomato variety in technological maturity of plants.

The object of the study is the fruit detacher with non-symmetric angular oscillations (Fig. 1). It consists of a Chalmers pulse generator (2, 3, 4, 5, 6), shaker drum with fingers (7, 8), grate (9), one-way roller clutch with buffer (10, 11, 12, 13, 14) and electric motor (1).

The electric motor (1) drives the Chalmers generator, which converts rotation of central gear (2) into angular oscillations of a carrier (6) and shaft (7). Its fingers (8) perform angular oscillations that are composed of consecutive rotations in two directions - towards input and towards output of the detacher. The angular amplitude towards output is larger than that towards input, therefore the oscillation is of asymmetric nature. This is due to the action of both one-way clutch (14) and spring (11) that reduces the angular amplitude towards input. It can be reduced to zero through pre-tensioning of the spring and by its replacing with another one of bigger constant of elasticity.

The developed fruit detacher allows smooth adjustment of oscillation frequency from 0 to 20 Hz, of angular amplitudes from 0 to 0.1 rad, as well as of ratio between their magnitudes in both directions of drum rotation during operation. This gives opportunity for a smooth change of both number of impacts and speed of moving plants toward device exit.

In operation, the overground parts of tomato plants are delivered on the grate (7) (Fig. 2). After sliding, stems are taken by fingers of shaft (3) and fruits pass under the grate (9) (Fig. 3). Fingers give angular oscillations to stems and simultaneously move them towards the exit of the detacher. The fruits leave stems due to inertial forces arising in them by the transmitted oscillations. Tomato fruits fall into the bag (6) without being mechanically

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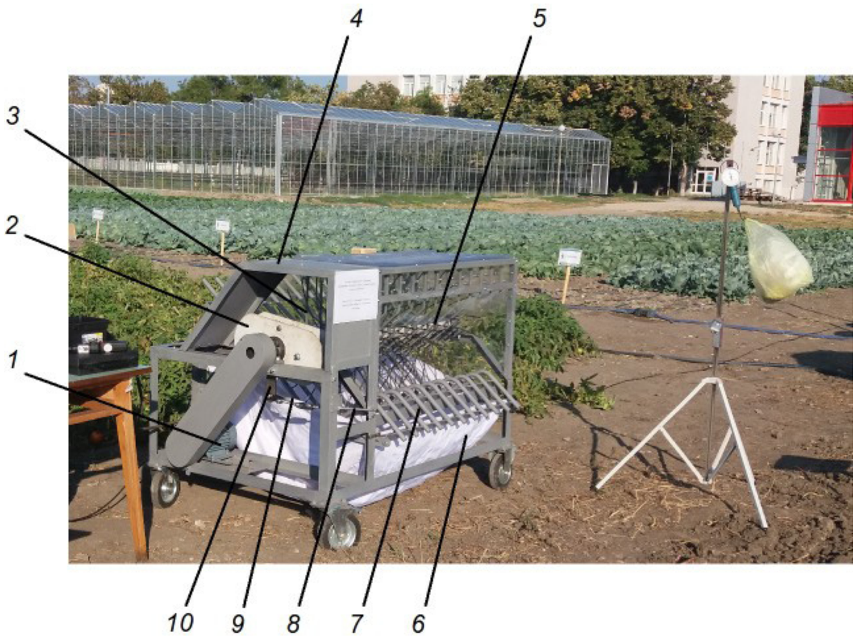

Fig. 2. Fruit detacher during removing fruits of table tomatoes at the field of Agricultural University, Plovdiv
1 – electric motor, 2 – pulse generator of Chalmers, 3 – shaker drum, 4 – lid, 5 – passive cleaners, 6 – bag, 7 – grate, 8 – tensioning screw, 9 – spring, 10 – one-way clutch

Fig. 3. Position of tomato fruits towards the grate of fruit detacher.

damaged, because they are not in contact with the oscillating fingers. This makes the developed detacher suitable for removing fruits from plants of table tomato varieties. Clearly, in a real harvester the bag has to be replaced with a conveyor.

MATERIAL AND METHODS

The studies were carried out with table tomato varieties. Plants were in technological maturity which is the most suitable for their mechanized harvesting (Moneruzzaman et al. 2009). The percentage of red to all fruits and their share to the overground part of the plants were determined for each tested variety just after the experiment.

Determination of qualitative indicators. Qualitative indicators of fruit detacher were investigated through a field experiment according to the experimental design B_2 with three replications (Mitkov 2011). The dependant factors were:
- percentage of removed fruits – D_f (%);
- percentage of admixtures among removed fruits – D_a (%);
- relative share of mechanically damaged fruits – D_d (%).

As controllable were selected the factors that most significantly influence the operating mode of the detacher and allow easy adjusting during operation. They are:
- The rotational frequency of the central gear – n (min^{-1}). It determines the oscillation frequency of Chalmers generator and shaker drum – f (Hz).
- The initial elastic moment of one-way clutch – M_{el_0} (Nm). Its values were calculated according to the Eq:

$$M_{el\_0} = \frac{k_{el} \times l}{r} \tag{1}$$

where: k_{el} – elastic constant of spring (Nm·rad^{-1}); l – stretching of spring (m); r – length of clutch lever (m)

The rotational frequency of central gear was varied through the electric motor (1) which is controlled by aSchneider Electric – ATV12HU22M2 inverter (www.mouser.bg). The initial elastic moment of clutch was changed by stretching the spring (11) through screw (10) (Fig. 1). Coded and

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Table 1. Controllable factors at assessment of fruit detacher qualitative indicators

Code	First factor		Second factor	
	n (min^{-1})	n (Hz)	l (mm)	M_{el_0} (N·m)
–1	400	6.7	0	0
0	600	10	7	1.0
+1	800	13.3	14	2.0

n – rotational frequency of the central gear; l – stretching of spring; M_{el_0} – initial elastic moment of one-way clutch

Table 2. Parameters of the shaker

Parameter	Dimension	Value
Mass of planet gears with weights	kg	6.25
Planet gear moment of inertia	kg·m^2	0.03381
Eccentricity – e	mm	92.5
Joint moment of inertia of carrier and shaker drum	kg·m^2	0.3834
Axle distance – b	mm	32
Elasticity constant of spring – k_{el}	Nm·rad^{-1}	0 ÷ 30

natural values of controllable factors are presented in Table 1. Remaining parameters of the shaker were maintained equal to those in Table 2.

After each experimental replication, fruits and impurities from the bag (6) were separated manually and weighed. Fruits remaining attached to stems were removed by hand; after that the percentages D_f and D_a were calculated. The share – D_d was determined through the amount of rotten fruits, one week after the experiment. Experimental data were subjected to regression analysis at a level of significance a = 0.05 using the Statistica 10 software (www.statsoft).

Determination of quantitative indicators. The main quantitative indicators of fruit detacher are both its productivity and torque of shaker drum. They were determined by numerical experiments conducted by a virtual instrument (Fig. 4), developed in the LabView environment (www.ni.com/labview) and based on an accurate analytical model (Ruschev et al. 2017).

The productivity of fruit detacher was calculated by following formulas:

$$q_s = \frac{m_s}{l_f} \times v_s \quad (2)$$

$$q_f = 10^{-2} q_s \Delta_f \quad (3)$$

where: q_s – productivity of over-ground part of tomato plants (kg·s^{-1}); q_f – productivity of tomato fruits (kg·s^{-1}); m_s – mass of over-ground part of tomato plants in fruit-removing area (kg); l_f – length of zone for removing fruits (m); v_s – speed at which plants pass the zone for removing fruits (m·s^{-1}); D_f – average percentage of fruit mass in one plant (%)

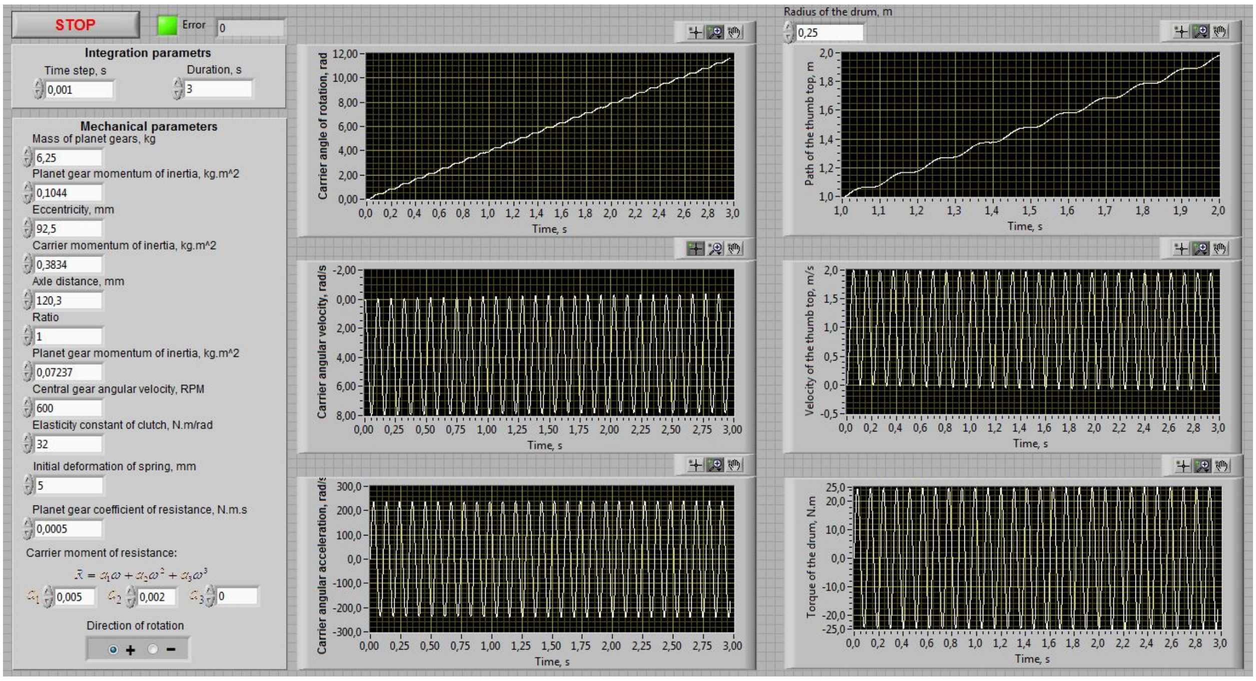

Fig. 4. Virtual instrument for determining the parameters of the shaker

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Table 3. Levels of controllable factors at determining velocity v_s

Code	n (min^{-1})	d (m)
–1	400	0.4
0	600	0.6
+1	800	0.8

n – rotational frequency of central gear; d – diameter of shaker

The parameter m_s was determined through average mass of one plant and their number in the zone for removing fruits. A numerical experiment according to plan B_2 with controllable factors (diameter of shaker – d and the rotational frequency of central gear – n) was carried out for determining the velocity v_s. It was obtained by dividing the length of zone for removing fruits (l_f) by the time for passing it. The controllable factors are presented in Table 3 and remaining parameters were maintained equal to those in Table 2.

The max. torques in both directions of rotation M_1 and M_2 of shaft (7) depend on the rotational frequency of central gear – n, the mass of weights (4) and their eccentricity – e (Fig. 1). Their influence was investigated through other single-factor numerical experiments using the mentioned virtual instrument.

RESULTS AND DISCUSSION

The experiments were conducted at the experimental fields of the Agricultural University - Plovdiv with plants of table tomatoes varieties 'Tomsk' and Torbay, which are selection by the Bejo company (www.bejoseeds.com). During experiments both varieties were in technological maturity. The ratio of mass of fruits to mass of the over-ground part of plants for the 'Tomsk' variety was 65.7% and for the Torbay variety it was 63.3%. The share of red fruits for the 'Tomsk' variety was 59.4% and for the Torbay variety 53.2%.

Qualitative indicators

For percentage of the removed fruits – D_f and percentage of admixtures – D_a the following regression equations were obtained:

For the 'Tomsk' variety:

$$D_f = 33.0121 + 0.1564n - 0.000095n^2 - 0.9746M^2_{el\_0} \quad (4)$$

with a coefficient of determination $R^2 = 0.93$, Fisher criterion $F = 8.43$ and probability $p_F = 0.052$

$$D_a = -29.7721 + 0.1433n - 0.0001n^2 - 0.9863M^2_{el\_0} \quad (5)$$

with $R^2 = 0.84$; $F = 4.35$ and $p_F = 0.036$.

For the 'Torbay' variety:

$$D_f = 33.0012 + 0.1515n - 0.0000898n^2 - 0.9688M^2_{el\_0} \quad (6)$$

with $R^2 = 0.95$; $F = 7.70$ and $p_F = 0.039$

$$D_a = -32.9871 + 0.1413n - 0.0001n^2 - 0.9912M^2_{el\_0} \quad (7)$$

with $R^2 = 0.83$; $F = 4.45$ and $p_F = 0.032$.

Results for the 'Tomsk' variety evidence that an increase of frequency n and decrease of elastic moment M_{el_0} lead to parabolic grow of the share of removed fruits – D_f from 76% to 98% as well as the share of impurities – D_a from 8% to 21% (Figs 5 and 6). At $n = 650 \div 800$ min^{-1} (f = 10.8 ÷ 13.3 Hz) and $M_{el\_0} = 0 \div 2.0$ Nm approximately coincidence of areas was observed where *Df* and *Da* had min. values. These results are due to the kinematics of the developed device and particularly:

– Increase of rotational frequency – n leads to growing of the speed and the acceleration of impacts on stems and hence of inertial forces acting on fruits.
– Small values of initial elastic moment M_{el_0} from 2.0 to 0 *Nm* increase the number of impacts on stems, regardless frequency n.

Theoretically, when $M_{el\_0} \neq 0$ then oscillations lose their symmetry due to reduction of angular amplitude towards detacher input. Besides, this amplitude loses its sinusoidal character and makes oscillations nonlinear (Fig. 4). Their acceleration grows more sharply than in harmonic oscillations and therefore causes more intensive detachment of fruits. The increase of M_{el_0} above 3 Nm leads to reduction of the number of impacts and to faster movement of stems in the zone for fruit removal. Otherwise, if there is no one-way clutch ($M_{el\_0} = 0$), then stems do not come out from the mentioned zone due to parity of amplitudes in both direction of drum rotation.

Resulting share of mechanically damaged fruits was 6.6%. It is equal to share of fruits that could not pass through the gaps of grate because of their large size and thus they were subjected to direct impacts of the fingers.

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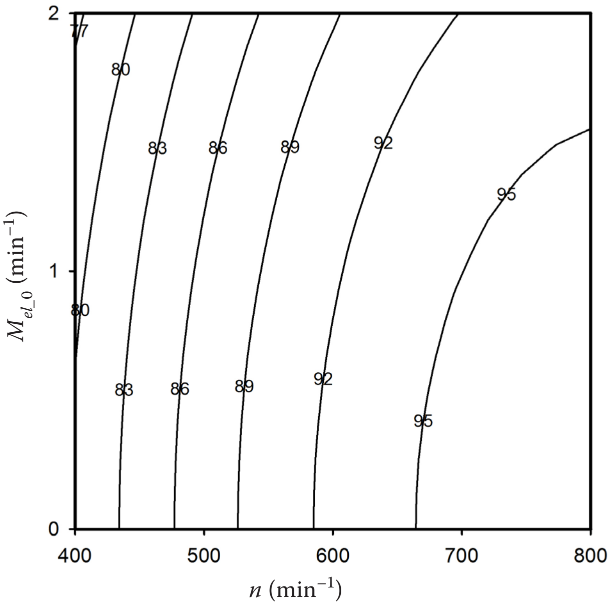

Fig. 5. Equal level lines for percentage of detached fruits – D_f from the 'Tomsk' variety

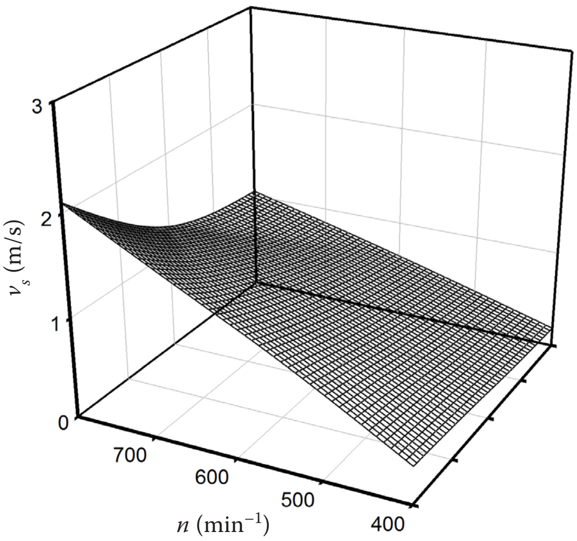

Fig. 7. The speed v_s with which plants pass the zone for removing fruits depending on the diameter of shaker drum – d and the rotational frequency of central gear – n at M_{el_0} = 2.0 Nm and k_{el} = 30 Nm·rad^{-1}

Results for the Torbay variety differ from those of the 'Tomsk' variety with values that are smaller than the statistical error of the study, which is explained by two reasons:

- The two tested varieties are at equal maturity and therefore the removal of fruits from stems requires approximately equal forces.
- The fruit detacher imparts vibration impacts that are suitable for removing tomato fruits in technological maturity.

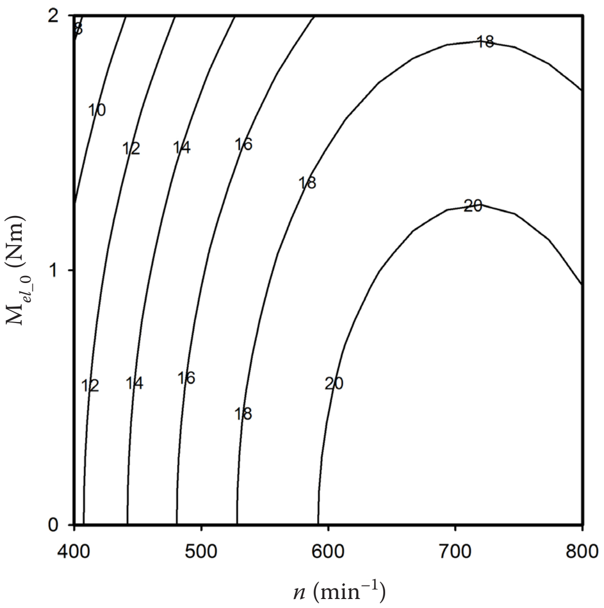

Fig. 6. Equal level lines for percentage of admixtures among removed fruits – Da from the 'Tomsk' variety

Quantitative indicators

The speed with which plants pass the zone for removing fruits depending on diameter of shaker drum – d and rotational frequency of central gear – n is presented in Fig. 7. Obviously, it changed from 0.28 to 2.1 m·s^{-1} for conditions of the experiment. The length of zone for removing fruits is l_f = 0.6 m. There can be located three stems with average mass m_s = 3.238 kg. Substituting these data in equation (2) shows that the detacher productivity for plants is in the range of 1.554 ÷ 11.650 kg·s^{-1}. Following application of equation (3), resultsin the values for the productivity for fruits from 0.827 to 6.921 kg·s^{-1} for each meter of detacher's working width. Its best qualities are seen at productivity of 2.460 to 4.621 kg·s^{-1}, which is lower than maximal by 67%. This result is explained by the necessary number of impacts to remove all tomato fruits from plants.

In order to achieve and maintain the speed – v_s, a torque for shaker drum is required to be sufficient for moving plants in fruit removing zone. The torque is influenced by the frequency of central gear, the mass of weights and their eccentricity in a similar way. Therefore, only an effect of frequency is represented, as it gives the greatest options for adjusting working mode of detacher during operation. The mass of weights and their eccentricity are

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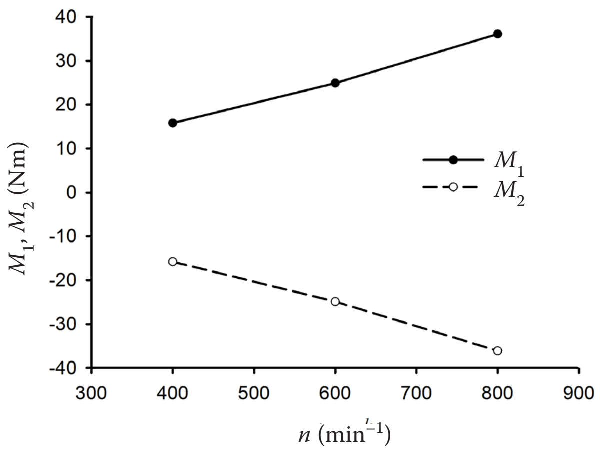

Fig. 8. Influence of the frequency of central gear – n on torques of shaker drum in both directions of rotation – M_1 and M_2

maintained constant and equal to those given in Table 2.

The torque values in both directions of shaker drum rotation – M_1 and M_2 are shown in Fig. 8. For developed fruit detacher they changed from ± 15.8 Nm to ± 36.1 Nm when frequency of central gear n increased from 400 (f = 6.7 Hz) to 800 min^{-1} (f = 13.3 Hz). At these torque values, the fingers act on stems with forces of 52.7 to 120.3 N that are sufficient to move them in zone for fruit removing.

Factors determining the operation of fruit detacher can be divided into two groups. The first group includes the diameter of shaker drum – d and the clutch elastic constant – k_{el}, which are determined at a design stage. In the second group there are the rotational frequency of central gear – n and the initial elastic moment of clutch – M_{el_0}, which are used for adjusting the operation mode of the detacher.

It should be noted that the aforementioned indicators are achieved by only one shaker drum, which simultaneously performs the removal of fruits and the movement of plants towards the exit of device; it therefore drops out the necessity of a conveyor for moving plants in fruit removing zone. Moreover, the developed device solves the problem of technical reliability of existing shaker conveyors.

CONCLUSION

The developed detacher removes over 95% of fruits of table tomato varieties 'Tomsk' and 'Tobray', without damaging them mechanically at a vibration frequency from 10.8 to 13.3 Hz and an initial elastic moment of the clutch from 0 to 2.0 Nm. In the mentioned operating mode, the shaker drum gives the plants angular accelerations from 87 to 123 rad·s^{-1} and forces from 52.7 to 120.3 N, which are sufficient for their displacement and for removing fruits from stems. The fruit detacher achieves productivity for over-ground part of tomato plants from 1.554 to 11.650 kg·s^{-1} and for fruits in the range of 0.827 to 6.921 kg·s^{-1} for every meter of its working width. The best quality indicators of the developed detacher are observed at the productivity of 2.460 to 4.621 kg·s^{-1}. Developed fruit detacher can be integrated into harvester for table tomato varieties and to be tested for inertial removal of other fruits.

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