Indices of flow fruit detacher with angular vibrations at inertial threshing of sesame

Stoyan Ishpekov[1*], Rangel Zaykov[1], Petar Petrov[1], Dechko Ruschev[2]

(1Agricultural University - Plovdiv, Department of Mechanization, Bulgaria;

2Technical University - Sofia, Plovdiv Branch, Department of Mechanics, Plovdiv, Bulgaria)

Abstract: An experimental stand of flow rotational fruit detacher with asymmetric angular vibrations has been developed at the Agricultural University - Plovdiv (Bulgaria). It is designed to detach fruits and seeds from the plants via inertial way. The aim of the presented paper was to evaluate the main indices of the flow fruit detacher at inertial threshing of non-dehiscent sesame varieties. The results indicated that the detacher threshes over 95% of seeds without reducing their germination. The seed moisture content is from 12.2% to 13.3%, which is two times higher than recommended for harvesting sesame with grain harvester. The portion of the impurities in the threshed mixture is from 20.99% to 38.41% depending on varieties. The detacher has reached 225 times higher threshing productivity than single person, but it is 1.4 times lower than the thresher of the grain harvester.

Keywords: sesame harvesting, mechanization, selection, damage saving technology

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1 Introduction

Mechanized harvesting of sesame seed is an unsolved problem worldwide (Langham D. R. and T. Wiemers, 2002). For its solution are conducted research and development activities in two directions:

- Selection of sesame varieties, which do not squander their seeds at maturation (Stamatov S., M. Deshev, 2014).

- Adaptation of existing and development of new machines and technologies for harvesting the seeds (Ishpekov S. et al., 2015a; Kenanska A. et al., 2014; Lee K. et al., 2015; Yilmaz D. et al., 2008).

The selected non-squandering sesame genotypes are two groups. The first group of varieties has completely closed capsules at maturation. The second group opens only tip of the capsules and hold the seeds to the placenta at maturation. Closed capsules genotypes have less yields and maintain higher humidity of the seeds at maturation, which is a prerequisite for their mechanical damaging at harvesting. For regions with humid climate during harvesting are recommended non-dehiscent varieties.

Second direction studies have been conducted in adapting of existing threshers and grain harvesters for harvesting of sesame seeds. These machines thresh the seeds by breaking the capsules which is applicable in regions with dry and warm climate.

A flow rotational fruit detacher with asymmetric angular vibrations has been developed at the Agricultural University - Plovdiv (Bulgaria) (Ishpekov S. et al., 2015b). It is designed to detach of fruits and seeds from the plants via inertial way. For this reason it does not require destruction of sesame capsules for threshing the seeds (Ishpekov S. et al., 2015c).

The purpose of the study is to determine the indices of the flow fruit detacher with asymmetric angular vibrations at inertial threshing of non-dehiscent sesame varieties.

2 Materials and methods

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***Corresponding author: Stoyan Ishpekov,** Department of Mechanization, Agricultural University -Plovdiv 4000, BULGARIA. E-mail: sishpekov@abv.bg

The indices of the flow fruit detacher have been investigated through an experimental stand (Figure 1). The main unit of the stand is a rod spindle 5, which performs asymmetric angular vibrations. They are created by the rotational-vibration generator (RVG) which consists of a pulse Chalmers mechanism, one-way clutch 3, spring 4 and stretching screw 6 (Ishpekov S. et al., 2015b; Lester W.T., 2009).

The electric motor 2 drives RVG 1, which converts the rotation of the central wheel into angular vibrations of the carrier and the spindle 5. Its rods perform angular vibrations which are composed of consecutive spins in two directions - toward the entrance and toward the exit of the stand. The angular amplitude toward the exit is larger than amplitude toward the entrance therefore the vibrations have asymmetric character (Ruschev D. et al., 2016). It is due to the action of the one-way clutch 3 and spring 4, which reduce angular amplitude toward the entrance of the stand. This amplitude can be reduced to zero by stretching the spring by means of the screw 6 and through increase of its elastic constant.

In operation the stems are fed over grill 8 manually and then fall between rods of the spindle 5. It gives the stems angular vibrations and simultaneously moves them toward the exit of the stand. Due to the vibrations the seeds detach from the capsules and fall into the bag 7. The stems 9 leave the stand without being deformed.

In this case, the seeds detachment is mainly due to the inertial forces that are created and transmitted to stems and capsules through the rod spindle 5. Therefore, this kind of threshing of the seed is called inertial. It does not require the breaking of the capsules for detaching the seeds, which is a significant difference from the threshing in the grain harvesters.

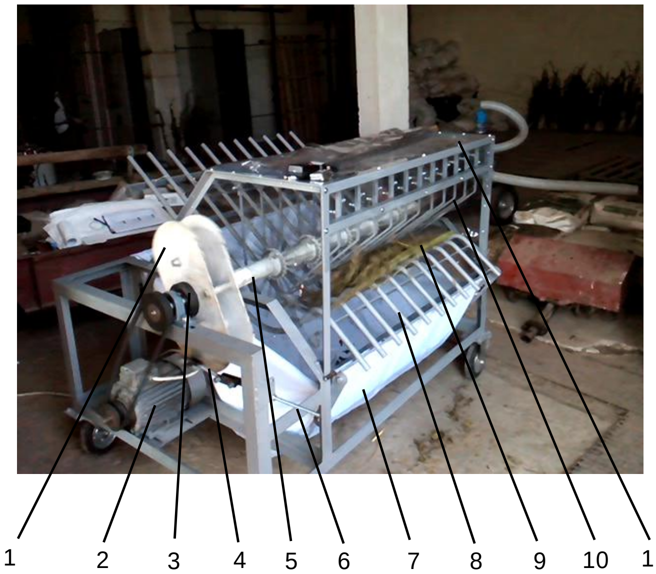


Figure 1 Experimental stand of a flow fruit detacher at inertial threshing of sesame

1 - pulse Chalmers mechanism, 2 - electric motor, 3 - one-way clutch, 4 - spring, 5 - rod spindle,
6 - stretching screw, 7 - bag for threshed material, 8 - grill, 9 - sesame stems, 10 - cleaners, 11 - lid

The main qualitative and quantitative indices of the experimental stand have been investigated at inertial threshing of sesame. Experiments have been conducted with three non-dehiscent sesame varieties called Aida, Nevena and Valya. They open only the top of capsules and the placenta retains seeds up to full maturity (Stamatov S., and M. Deshev, 2014). The varieties had been selected at Institute of Plant and Genetic Resources - Sadovo (Bulgaria), where have been determined the indices of the experimental stand.

2.1 Method for investigating qualitative indices of the stand

The controllable factors have been selected according to the results from preliminarily experiments. They showed that the speed of the central wheel influences is similar to the spindle diameter. Moreover, the elastic constant of clutch influences as its initial elastic momentum (Ishpekov S. at al, 2015b). That is why controllable factors have been selected so that to allow easy adjustment of the operating mode of the stand, namely:

- The rotation frequency of the central wheel of the RVG - n, min^{-1};

- Initial elastic momentum of the clutch - $M_{el\,0}$, $N\,m$.

The angular speed of the central wheel is changed through the speed of the asynchronous three-phase electric motor 2, which is controlled by frequency inverter Schneider Electric - ATV12HU22M2. The initial elastic momentum of the clutch is changed by stretching the spring 4 by means of the screw 6 (Figure 1).

An experiment according to design B_2 with a measurement in the centre and with three replications has been conducted (Mitkov At., 1993). The natural and coded values of controllable factors are presented in Table 1. The remaining parameters of the spindle and RVG are maintained equal to those of Table 2.

Table 1 Controllable factors at investigating quality indices of the stand

code	n (min^{-1})	M_{el_0} $(N\ m)$
-1	120	0
0	420	0.8
+1	720	1.6

Table 2 Parameters of the spindle and RVG

parameter	dimension	value
Mass of central gear	kg	5.49
Planet gear moment of inertia	$kg{\cdot}m^2$	0.03138
Eccentricity	mm	92.5
Carrier moment of inertia	$kg{\cdot}m^2$	0.43612
Axle distance	mm	120.3
Elasticity constant of spring	$N{\cdot}m{\cdot}rad^{-1}$	32
Initial deformation of spring	mm	0÷15

Three qualitative indices have been investigated:

- Portion of the detached seeds toward the average yield - D_c, %;

- Portion of the impurities towards the detached seeds - D_a, %;

- Portion of mechanically damaged seeds due to threshing - D_d, %.

The quality indices D_c and D_a have been determined from the mixture which is collected in the bag below the grill 8 after each replication. The seeds have been separated from the impurities through two sieves with different openings. The mass of seeds and impurities have been calculated toward one plant, then has been calculated their portion in relation to the yield.

A cross check of the values of D_c has been done by subtracting from the yield of the quantity of seeds remaining in the processed stems. These seeds have been detached through manual crushing of the capsules.

The mechanical damage of the seeds has been assessed through their germination. Free of impurities seeds have been used, threshed at the most intense operating mode of the stand. The results are compared to the germination of seeds which have been threshed manually and by grain harvester.

The experiments are carried out with 100 stems of each tested sesame variety. They have been cut from the roots before opening tip of the capsules and kept indoors. Qualitative indices of the stand are investigated a day after opening tip of the capsules. During the experiments, the seeds moisture has been determined by the weight method.

Other 100 sesame plants grown in the same spot have been used to determine the yield of seeds, which later on is calculated toward one plant. Six randomly selected stems from each variety have been processed at every replication.

Experimental data have been processed via regression analysis by the method of least squares at significance level $\alpha = 0.05$.

2.2 Method for investigating quantitative indices of the stand

The main quantitative indices of the stand are the productivities for stems and for seeds. They are calculated by the following formulas:

$$q_s = \frac{m_s}{l_t}.v_s \qquad (1)$$

$$q_c = 10^{-2} q_s \Delta_c \qquad (2)$$

where:

m_s is the mass of stems in the area of threshing of the stand, kg;

l_t - the length of the threshing area, m;

v_s - the speed with which the stems pass the area of threshing, $m \cdot s^{-1}$;

q_s - the stand productivity for stems, $kg \cdot s^{-1}$;

q_c - the stand productivity for seeds, $kg \cdot s^{-1}$;

Δ_c - the average portion of seeds in one stem, *%*.

The mass m_s has been determined by the average mass of a stem and their number in the area of threshing.

The speed v_s depends on the following parameters:

- The diameter of the rod spindle - *d*, *mm*;

- The oscillation frequency of the spindle, which is equal to the rotation frequency of the central wheel of RVG - *n*, min^{-1}.

- The elastic constant of the clutch - k_{el}, $N \cdot m \cdot rad^{-1}$;

- The initial elastic momentum of the clutch - $M_{el\,0}$, $N \cdot m$.

The influence of mentioned parameters of the spindle and the clutch on the velocity v_s have been investigated separately through two numerical experiments. They have been conducted according to experimental design B_2 with a measurement in the centre and with three replications (Mitkov At., 1993). The experiments have been performed with a virtual instrument in environment of the software LabView (Ruschev D. et al., 2016). The virtual instrument calculates velocity v_s trough the length of arc which the tip of one rod passes for ten seconds.

The natural and coded values of controllable factors are presented in Table 3. The remaining parameters of the spindle and RVG are maintained equal to those of Table 2. The results are presented by lines of equal level.

Table 3 Controllable factors at investigating velocity v_s

code	*n* (min^{-1})	*d* (*m*)	k_{el} ($N \cdot m \cdot rad^{-1}$)	$M_{el\,0}$ ($N \cdot m$)
-1	120	0.4	0	0
0	420	0.6	20	0.8
+1	720	0.8	40	1.6

2.3 Comparison of stand indices to other ways of threshing sesame

The indices, obtained by the stand, grain harvester and indices of manually threshing of sesame from one variety and equal moisture of the seeds have been compared. Portion of the detached seeds - D_c, their purity - D_a and germination, as well as the stand productivity for stems have been compared.

3 Results and discussions

3.1 Qualitative indices of the stand

Regression equations for proportion of seeds D_c and proportion of impurities D_a *in* the threshed mixture, depending on the rotation frequency of central wheel *n* and the initial elastic momentum $M_{el\,0}$ have been obtained.

For Aida variety with 13.3% moisture content of the seeds the following regression equations have been obtained:

$$D_c = -16.5040 + 0.1718n - 0.0001n^2 + \\ +1.5606M_{el\_0} - 25.1421M^2_{el\_0} + 0.0194.n.M_{el\_0},$$

With coefficient of determination R^2=0.94, Fisher criterion F=8.50 and probability p_F=0.054;

$$D_a = 87.4074 - 0.1662n + 0.0001n^2 - 54.2370M_{el\_0} + \\ +10.4344M^2_{el\_0} + 0.0591.n.M_{el\_0}$$

,

R^2=0.92, F=5.5 and p_F=0.066.

For Nevena variety with 13.1% moisture content of the seeds:

$$D_c = -16.4400 + 0.2066n - 0.0002n^2 + 24.9144M_{el\_0} - \\ -12.5721M^2_{el\_0} + 0.0377.n.M_{el\_0}$$

,

R^2=0.93, F=6.35, p_F=0.063;

$$D_a = 102.7439 - 0.2091n + 0.0001n^2 - 60.4018M_{el\_0} + \\ +5.2788M^2_{el\_0} + 0.0910.n.M_{el\_0}$$

,

R^2=0.95, F=5.1, p_F =0.051.

For Valya variety with 12.2% moisture content of the seeds:

$$D_c = -19.6575 + 0.2933n - 0.0003n^2 + 10.3985M_{el\_0} - -5.4061M_{el\_0}^2 + 0.0345.n.M_{el\_0}$$
,

R^2=0.96, F=9.01, p_F=0.05.

$$D_a = 46.41238 - 0.13181n + 0.00017n^2 + 10.02941M_{el\_0} -9.36318M_{el\_0}^2 + 0.00494.n.M_{el\_0}$$
,

R^2=0.93, F=6.23, p_F=0.057.

Increasing of $M_{el\ 0}$ and n leads to portion grow of the detached seeds - D_c from 10% to 95% for Aida variety (Figure 2). The portion of impurities in thresh mixture - D_a varies between 20% and 30% at n = 400 ÷ 720 min^{-1} and $M_{el\ 0}$ = 0.6 ÷ 1.6 $N{\cdot}m$. It increases up to 70% at reduction the controllable factors to n= 120 min^{-1} and $M_{el\ 0}$=0 and is also due to a reduction of D_c below 20%.

The results showed that impacts causing the maximum of D_c do not lead to the maximum of D_a (Figures 2 and 3). The maximum values of D_a have been obtained at the low levels of controllable factors - $n \leq 200$ min^{-1} and $M_{el\ 0}$ =0, achieved when the clutch is off.

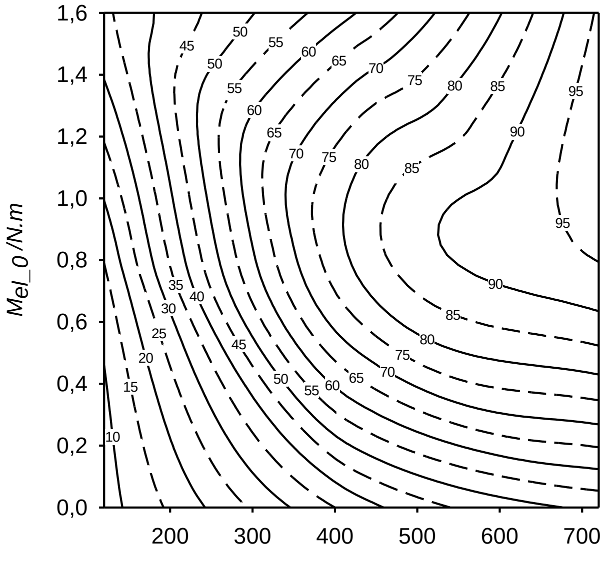


Figure 2 Equal level lines for the portion of detached seeds - D_c% with 13.3% moisture content from Aida variety depending on rotation frequency of the central wheel - n and initial elastic momentum of the clutch - $M_{el\ 0}$

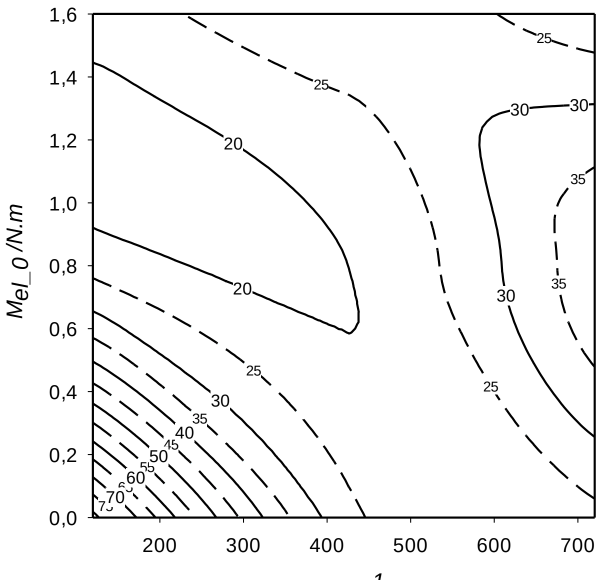


Figure 3 Equal level lines for the portion of impurities D_a% in threshed mixture for Aida variety depending on rotation frequency of the central wheel - n and initial elastic momentum of the clutch - $M_{el\ 0}$

Regression equations and graphs for the other tested varieties are similar to Aida. They differ in the extreme values of D_c and D_a, here below presented in Tables 4 and 5. Obviously D_c has a minimum when the rotation frequency n = 120 min^{-1} and the clutch is off ($M_{el\ 0}$=0) for all tested varieties. The maximum of D_c is seen at n=720 min^{-1} and $M_{el\ 0}$=10 $N{\cdot}m$. In this operating mode, rods impact on the stems are with maximal speed 3.6 $m{\cdot}s^{-1}$ and maximal angular acceleration 150 $rad{\cdot}s^{-2}$.

The portion of impurities D_a affects on the clearing of seeds after threshing and often limits the productivity of the harvester. In the present study this portion varies in a wide interval - from 11.61% to 83.86% (Table 5).

Table 4 Extreme values for the portion of the threshed seeds

variety	Operational mode		D_c ,%	
	n (min^{-1})	$M_{el\ 0}$ ($N{\cdot}m$)	min	max
Aida	120	-	7.77	-
	720	10	-	95.75
Nevena	120	-	7.42	-
	720	10	-	97.33
Valya	120	-	13.16	-
	720	10	-	80.58

Table 5 Extreme values for the portion of the impurities in the threshed mixture

variety	Operational mode		D_a ,%	
	n (min^{-1})	$M_{el\,0}$ ($N{\cdot}m$)	min	max
Aida	120	-	-	81.63
	420	5	19.86	-
Nevena	120	-	-	83.86
	120	10	11.61	-
Valya	720	5	-	65.63
	120	5	17.36	-

The mode which gives maximal D_c is most important for the practice. This mode is at n=720 min^{-1} and $M_{el\ 0}$=10 $N{\cdot}m$ when the following portions of impurities have been obtained in the threshed mixture:

- For variety Aida - D_a = 20.99%;
- For variety Nevena - D_a = 38.41%;
- For variety Valya - D_a = 22.17 %.

The extreme values of D_a have been observed at different operational modes for the three tested varieties (Table 5). Provided that the moisture of their seeds has not deviated by more than 1.1%, this result is explained by different effort to release the seeds, which is a varietal characteristic.

Aida variety has a minimum value for the portion of threshed seeds D_c = 7.77%, while the variety Nevena - D_c = 7.42% (Table 4). These values are significantly smaller than the corresponding value for variety Valya - D_c = 13.16%. Apparently the two varieties retain more seeds in capsules before stems entering in stand. The maximum values of D_c for variety Aida and Nevena are 95.75% and 97.33% respectively, but for the variety Valya they reach 80.58%.

Earlier study indicated that the variety Valya releases part of seeds at weak mechanical impact, but another part does not release even under strong shock (Ishpekov S., 2015c). Moreover, in the threshed mixture fall capsules and small branches, while at threshing of other varieties it is not observed. These results indicate that Valya is less suitable for inertial threshing in comparison with the other two varieties.

The parameters of impact on stems affect the portion of the detached seeds - D_c as follows:

- Increasing the rotational frequency n causes a growth of inertial forces acting on seeds due to increasing the frequency of oscillation. That is why almost all seeds leave the capsules at high values of n.

- The initial elastic momentum $M_{el\ 0}$ violates the symmetry of the angular oscillation of rods, because it reduces their angular amplitude towards the entrance of the stand (Ruschev D. et al., 2016). This leads to a reduction of the number of impacts and faster removal of stems from the area of threshing. Conditioned $M_{el\,0}$=0 up to n=200 min^{-1}, stems not leave the threshing area, because the torque of the rod spindle is not sufficient.

The raising of $M_{el\ 0}$ from 0.2 to 0.9 $N{\cdot}m$ leads to growth of detached seeds portion D_c, because the angular oscillations have become bidirectional and the number of impacts on stems has increased in the area of threshing. At $M_{el\,0} \geq 0.9$ $N{\cdot}m$ the portion of detached seeds decreases because the amplitude of the rods toward exit tends to zero and the number of impacts on stems has decreased.

The portion of the detached seeds - D_c, obtained by manually crushing of the capsules and through the methodology applied differs less than ± 2.6%. This result is important for the practice, because the methodology for determining D_c through manually crushing the capsules seems accurate, but requires a lot of time for implementation. The long time experiment causes a reduction in the strength of the connection between the seeds and placenta, due to lowering their moisture content. Therefore, the long time experiment leads to a systematic error in the study of quality indices for threshing of non-dehiscent sesame varieties.

The results for germination of seeds, which have been thrashed at n=720 min^{-1} and $M_{el\ 0}$=10 $N{\cdot}m$ are presented in Table 6. Obviously, this result does not differ significantly from the germination of seeds which have been threshed manually. This means that the stand does not damage mechanical seeds at their inertial threshing in technological maturity. Decreasing germination of seeds by 1% is seen only for Valya variety, although they have been threshed at the lowest moisture. This may be due to the fact that its seeds are 14.3% heavier than the seeds of the other two tested varieties. It is possible that the mass of seeds influences their mechanical damage in inertial threshing, but it must be confirmed through further research.

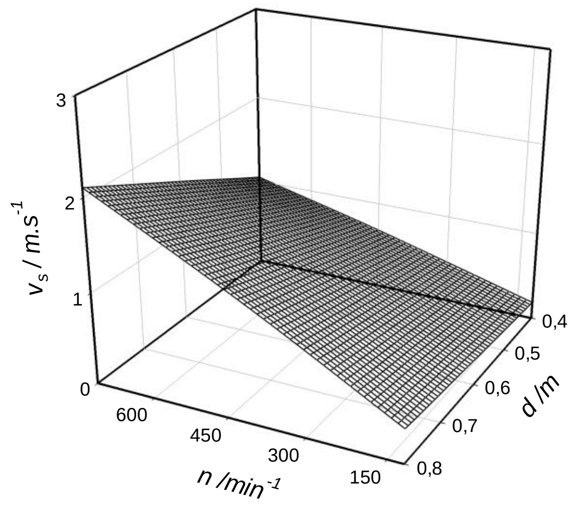
Table 6 Germination of the thrashed seeds

variety	Moisture content of seeds, d.b.,%	Germination, % by stand	manually
Aida	13.3	98	98
Nevena	13.1	98	98
Valya	12.2	97	98

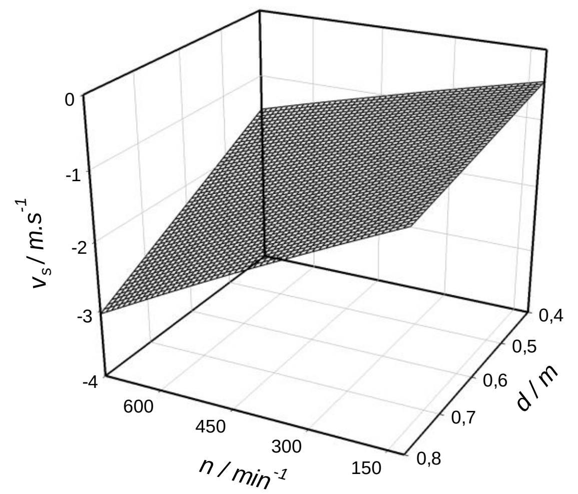
3.2 Quantitative indices of the stand

The change of v_s (velocity of stems while passing through area of threshing) depending on the rotation frequency of central wheel *n* and spindle diameter *d* is given in Figure 4. The investigated speed varies, depending on two ways of clutch operation, not only in absolute value, but also in sign. It is changed from 0.19 to 2.1 $m.s^{-1}$ at matching rotation directions of the central wheel and actuation of the clutch. When their directions are opposite then the change is from -0.45 to -3.05 $m{\cdot}s^{-1}$. Minimum absolute values of v_s have been obtained at conditioned diameter of the rod spindle d = 0.4 *m*, central wheel frequency of rotation n = 120 min^{-1} and at maximum absolute values d = 0.8 *m* and n = 720 min^{-1}.

At one-row harvesting the speed v_s should be equal to the speed of the harvester in order to prevent congestion or insufficient supply of stems. This condition is satisfied if the speed of the harvester varies from 0.19 to 3.05 $m{\cdot}s^{-1}$.



a) At matching directions of rotation of the central wheel and actuation of the clutch



b) At opposite directions of rotation of the central wheel and actuation of the clutch

Figure 4 Graph of stems velocity v_s, depending on the rotation frequency of the central wheel *n* and spindle diameter *d* at initial elastic momentum $M_{el\ 0}$=5 $N{\cdot}m$ and elastic constant of the clutch k_{el} = 32 $N{\cdot}m{\cdot}rad^{-1}$

The developed stand has zone of threshing length l_t=0.6 *m*, which can contain 15 stems with total mass m_s = 0.738 *kg*. Using formula 1, the following maximum productivities for stems have been calculated:

- q_s =2.58 $kg{\cdot}s^{-1}$ at matching directions of rotation of the central wheel and actuation of the clutch;

- q_s=3.75 $kg{\cdot}s^{-1}$ at opposite directions.

While the seeds are 12% of stems mass at technological maturity, the productivities of seeds are

0.31 and 0.45 $kg \cdot s^{-1}$, depending on the operation way of central gear and clutch, respectively.

The experimental results showed that the investigated factors can be divided in two groups. The first group includes diameter of the rod spindle d and elastic constant of the clutch - k_{el}, which are determined at design stage. Speed of central wheel - n and initial elastic momentum of the clutch - $M_{el\,0}$ are in the second group. They can be used for adjusting the operation mode of the stand.

3.3 Comparison the indices of the stand and other ways of sesame threshing

The results of threshing of Aida variety in three ways - manually, by Wintersteiger grain harvester and by developed stand are presented in Table 7. The stand achieved 95.8% portion of the threshed seeds which is 8.7% higher than that of the grain harvester and 39.5% higher than by manual threshing. The portion of impurities in the threshed mixture by manual threshing is 18.7% which is 4.5% lower than stand and 37.8% lower than the grain harvester.

Table 7 Threshing indices for Aida variety with 13%moisture content of seeds

Way of threshing	D_c %	D_a %	Germination %
manually	56.3	18.7	98
Wintersteiger	87.1	56.5	71
stand	95.8	23.2	98

The grain cleaner CM - 0.15 increases the purity of seed, threshed manually or by the stand up to 95%. It also increases the purity of the seeds that has been threshed by the grain harvester, but up to 71.7%. The remaining impurities in threshed mixture cannot be separated by the grain cleaner.

Germination of seeds with 13% moisture content that have been threshed manually and by the stand is equal. This means that the stand does not damage mechanically seed at their inertial threshing. The seed looses 27% germination when they have been threshed by the grain harvester. Moreover, the classic threshing causes the release of oil from seeds, which is mixed with various particulate pollutants. This makes cleaning threshed seeds difficult, worsens their commercial look and even changes their colour (Figure 5).

Figure 5 Sesame seeds threshed by the stand (on the left) and by the grain harvester Wintersteiger (on the right) and cleaned by the grain cleaner CM - 0.15

The results for threshing productivity of Aida variety in three ways are presented in Table 8. The compared ways are:

- Manual threshing by one person;
- Threshing by grain harvester Wintersteiger, which threshing drum has a width of 1.45 *m*;
- Inertial threshing by the flow fruit detacher with working width of 1.3 *m*.

The developed stand and the thresher of the harvester Wintersteiger have approximately the same working width. However the combine achieves 1.58 times higher performance of sesame threshing. The threshing productivity of single person is 355 times lower than grain harvester and 225 times lower than stand.

After reducing the productivity of both threshers to one meter working width we receive the following results. The reduced productivity of the combine thresher is 0.49 $kg \cdot s^{-1} \cdot m^{-1}$ and of the developed stand is 0.35 $kg \cdot s^{-1} \cdot m^{-1}$. The difference is 1.4 times and is due to the different principles of threshing in both mechanisms.

Table 8 Productivity at threshing of variety Aida with 13%moisture content of seeds

Way of threshing	Productivity($kg \cdot s^{-1}$)
manually by single person	0.002

by Wintersteiger	0.71
by the stand	0.45

The main advantage of the stand is achieving mentioned results at seed moisture content from 12.2% to 13.3%, which is two times higher than recommended for harvesting sesame with grain harvester (Langham D., 2002). This is an important prerequisite for mechanized harvesting of sesame seeds in regions with humid climate.

4 Conclusions

The developed flow fruit detacher threshes over 95% of seeds from the non-dehiscent varieties Aida and Nevena without reducing their germination. The portion of the impurities in threshed mixture is from 20.99% to 38.41% depending on varieties. The seed moisture content is from 12.2% to 13.3%, which is two times higher than recommended for harvesting sesame with grain harvester.

The stand reached 225 times higher threshing productivity than single person. The reduced to 1 *m* working width productivity of the grain thresher is 1.4 times higher than of the stand and is due to the different principles of threshing in both mechanisms.

Threshing of sesame seeds with 13% moisture content by grain harvester causes decreasing of their germination with 27%. The impurities in the threshed mixture are 56.5%, half of which does not allow separation by the conventional grain cleaner.

The stand achieves maximal portion of threshed seeds at rotation frequency of the central wheel 720 min^{-1} and initial elastic momentum 10 $N \cdot m$. These parameters are suitable and sufficient for mode adjustment of inertial threshing. In the mentioned working mode the rods give the stems maximal speed 3.6 $m \cdot s^{-1}$ and maximal acceleration 150 $rad \cdot s^{-2}$.

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