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Theoretical and experimental research into impact of threshing tools in combine grain harvesters on quality of cereal crop seeds

D. Derevjanko[1], I. Holovach[2], V. Bulgakov[2], V. Kuvachev[3] and J. Olt[4,*]

[1]Zhytomyr National Agroecological University, 7, Staryi Blvd, UA 10008 Zhytomyr, Ukraine
[2]National University of Life and Environmental Sciences of Ukraine, 15, Heroyiv Oborony street, UA 03041 Kyiv, Ukraine
[3]Dmytro Motornyi Tavria State Agrotechnological University, 18[B], Khmelnytsky Ave, UA 72310 Melitopol, Zaporozhye Region, Ukraine
[4]Estonian University of Life Sciences, Institute of Technology, Kreutzwaldi 56, EE 51006 Tartu, Estonia
[*]Correspondence: jyri.olt@emu.ee

Abstract. The theoretical and experimental research into the micro-damaging of cereal crop seeds in the process of their harvesting by combine grain harvesters in relation to the strains, forces and stresses imparted to them by the threshing tools has been carried out. The propagation of deformations and cracks in the seeds as well as the nature of their strength and the damage that is sustained, when the critical load is applied, have been investigated. It has been established that the onset of cracks, the direction of their propagation and their quantity in the bodies of grain seeds depends in the majority of cases on the direction of action of the external forces and the specifics of the seeds' internal biological properties. It has been established that the strength of the grain seed is, apart from the arisen cracks, also under the significant effect of the microtraumas in the germ, endosperm as well as the seed coat and shell. Theoretical calculations have been carried out on the PC and the effect that the drum and rotor threshing apparatus have on the deformation and damage sustained by cereal crop seeds has been substantiated. The said calculations and the obtained graphic relations support the results of the experimental investigations and prove that the macro- and especially micro-damage sustained by the seeds of winter wheat and rye is different, when they are threshed with the use of different types of threshing apparatus, which has a considerable impact on the final quality of the harvested cereal crop seeds. The results obtained in the experimental investigations, field and laboratory tests on the topic of the effect of mechanical loading on the sustained damage and quality of seeds indicate that the damage rate accounted for the work processes of the reaping and postharvest treatment of the cereal crop heaps of different winter wheat varieties with the use of rotor threshing apparatus is 3.1% as compared to the drum threshing apparatus – 6.4%, that is, 2 times lower. The total amount of the seeds with microtraumas collected in the hopper after threshing amounts to 23.0% and 54.0%, respectively, which is a significant difference. Similar results have been obtained in the experimental investigations on the effect of the equipment on the sustained damage and quality of seeds in the cleaning, chemical treatment and sowing of cereal crops.

Key words: damage, deformation, drum and rotor threshing apparatus, grain, quality, seed, strength.

INTRODUCTION

It is common knowledge that winter wheat, rye and other most important valuable cereal crops that occupy large areas of cultivated land play a significant part in, first of all, the food procurement. Therefore, it is of vital necessity to provide for the production of seeds with high quality indices (Harms & Meier, 2006).

In the second half of the last century, research scientists, plant breeders and producers proved and justified the fact that only high quality seeds, subject to all other provisions being equal, provide for the generation of the major part of the further harvest (Vasilenko, 1960). At the same time, the important fact to be pointed out is that there is certain lagging in the development, production and implementation of advanced equipment and technologies for the gathering and postharvest processing of the grain heap, the preparation, transportation, loading and chemical treatment of the seeds and their sowing (Derevyanko et al., 2012; Derevyanko, 2015; Golovvach et al., 2017).

The completed investigations (Drincha, 2006; Derevyanko et al., 2017) have proved that the reduction of the effect that the tools in the equipment have on the process of damaging the caryopses in the course of the performed work processes contributes to substantial improvement of the seed quality indices and growth of the cereal crop yield.

The macro- and micro-damaging, partial and complete breaking of caryopses result from their exposure to mechanical loading in many elements of the work process, starting from the gathering and processing and finishing by the later drilling.

The studies by Golovach et al. (2017), Derevyanko et al. (2012, 2015, 2017), Fadeyev (2015a, 2015b), Pugachov (1976), Strona (1974), Tarasenko (2003) and others indicate that the caryopses damage rate at the threshing stage exceeds 20%, while at the stages of the further processing of the grain heap and the preparation of the seeds for drilling the damage rate increases significantly, reaching sometimes levels of 60–80%.

According to the data by Drincha (1997, 2006), the rate of damage inflicted on the caryopses at the threshing stage amounts sometimes to 30–35%, while during their preparation even to more than 50%, depending on the moisture content and structure of the grain heap and the mechanical loading.

In recent years, considerable efforts were made by Fadeyev (2015a) for developing conceptually new cleaning and grading units and processing lines and implementing them in the production.

In the formation of the fundamental scientific basis for the theory of interaction between the working surfaces of mechanisms and various materials, including grain mass, a significant contribution has been Vasilenko (1960), Goncharov (1963), Chazov et al., 1981; Adams et al., (1993), Kutzbach et al., 1996; Beck (1999), Drincha (1997; 2006), Strona (1974), Maertens & De Baerdemaeker, (2003), Tarasenko (2003), Tischenko et al. (2011), Miu & Kutzbach, (2008) and Miu (2016).

The intensity of pressing the seeds down and, accordingly, their micro-damaging during the contact between the caryopses and the working surface of the screw, if considered in relation to the angle of helix, has the lowest value, when the said helix angle stays within the range of $\alpha = 5–10°$. When the helix angle exceeds 15°, the intensity of the growth is proportional to the angle of helix of the screw turns (Derevyanko, 2015, 2017).

The research by Derevyanko (2015 and 2017) proves that the intensity at which the seeds are pressed and, accordingly, the levels of micro-damage that are inflicted upon then during contact between the caryopses and the screw's working surface, when considered in relation to the angle of helix, has the lowest value when said helix angle remains within the range of α = 5–10°. When the helix angle exceeds 15°, the intensity of the growth of micro-damage is proportional to the angle of the helix in the screw's turns.

Thus, the profound and comprehensive research into the physical mechanical and biological features of seeds and the development of new technologies together with the modernisation of the tools in order to provide for the minimum amount of caryopses micro-damaging are the efforts that will ensure the production of high quality seeds in compliance with the agricultural engineering requirements and standards.

The aim of this study is to improve the quality of seed separation, and to reduce seed damage rates in all stages of the harvesting process where a grain harvester is used, by way of defining separator tool types and the operating modes in which they are used, and also by developing equipment that is needed for the implementation of such processes in production operations.

MATERIALS AND METHODS

The impact produced by the deformation, the strength and the damaging of cereal crop seeds during the work processes of their handling from the gathering to the drilling was investigated with the use of the standard methods based on the appropriate sampling and examination of seeds with the use of a tensile-compression test machine (Fig. 1) and a microscope (Fig. 2).

Figure 1. A tensile-compression test machine Istron 5969 being used to assess the grain's compression resistance.

The tensile-compression test machine (Fig. 1) has two drives which can be used to apply a load onto the seeds: one being electromechanical and the hand-operated. For precisely-defined loads, the study used manual loading. The electromechanical drive was used only for large differences in jaw positions. The machine can also store a graph in a PC showing the loading operation.

Tests that were carried out with the bursting machine were conducted in the following sequence: firstly, the seeds were placed into the bursting machine's jaws. The load could be applied along the longer or shorter axis of the seed. The seed was pressed until it burst. The pressure graph was stored and was then used as a basis for determining the maximum compression load. The maximum deviation for pressure measurements was 1%.

The following parameters were determined for the seeds, from the image on the microscope's screen (Fig. 2): the form of endosperm and germ, and the number of cracks and lesions on the endosperm and the germ. These parameters were stored on a PC.

The pneumatic separation unit with rubber coating was improved by introducing the rubber cladding of the casing, which contributes to the reduction of the seed damaging rate and the improvement of the quality of seeds.

Figure 2. Microscope AxioImager 2 for the macro and micro assessment of seeds.

The laboratory equipment for the investigation of the effect the mechanical factors have on the strength and damaging of the caryopsis was engineered.

The theoretical investigations and calculations were done by way of the mathematical modelling of the operation of equipment and the work processes, the application of the fundamental laws of mechanics and the state-of-the-art computation methods.

The experimental investigations were carried out under the laboratory and field conditions with the use of field-collected samples of the winter wheat variation, 'Odesskaya - 237' (reproduction - elite).

Once the experimental studies were being conducted, any random variations in the parameters being studied were assessed with the help of the variation coefficient $\hat{E}$. Based on its numerical value, the random variations of each parameter were assessed in relation to their average values:

$$\hat{E} = \frac{\sigma}{\bar{x}} \tag{1}$$

where σ – is the standard deviation of the parameter being studied; $\bar{x}$ – is the average value of the parameter being studied.

The use of the variation coefficient $\hat{E}$ in the studies made it possible to assess the dispersion of values without being constrained by the scale of the parameter or its unit of measurement. If the coefficient's value was below 10%, the parameter's variation was considered negligible, while within the range of 10% to 20% it was placed at 'medium', and above 20% it was classed as 'significant'.

In accordance with the developed procedure of experimental investigations, the number of samples taken in each type of combine at each frequency of rotation of its threshing drum or rotor and for each variety of wheat was at least 100. Further, in each of the taken samples the broken and micro-damaged caryopses were detected and recorded following also a specially developed procedure in laboratory conditions with the use of the AxioImager 2 microscope with a magnification ratio of 25–1,000. That said, it had been specially arranged that only grain material samples with the mass of 1,000 kernels equal to 42–54 grams were selected. In addition to that, the grain material in the samples was analysed with the use of the standard set of instruments with respect to its gluten composition, which varied within the range of 28–32%, and protein composition – 13.5–4.5%.

RESULTS AND DISCUSSION

In the performance of the work processes of gathering a cereal crop, processing the grain heap, preparing the seeds and drilling them, it is necessary to take into account the impact on the caryopsis of those external and internal factors, which give rise to stresses in the caryopsis. The stresses, in their turn, induce the active displacement of the whole organic mass and that causes the distances between individual parts to grow, which results in the weakening of the strength, that is, the reduction of the resistance to breaking of the whole caryopsis. It has also been established that in the further course of the work process, the gradual increase of the mentioned impact takes place, which leads to the growth of the distances between atoms and promotes the development of the conditions that are favourable for overcoming the potential barrier in the transition from the stable equilibrium condition to the unstable one, and later, the said distance between layers of atoms becomes very large, creating all prerequisites for the rise of a slit-shaped formation – the opening that does not close even after the load is removed.

However, the breaking of caryopses, i.e. the development of cracks in them, has to be viewed as a process that takes place in two stages: the rise of the conditions for the generation of the future crack, which implies the physical features of breaking, and the development of its propagation, which involves the fracture mechanics. The disintegration processes at each of these stages follow different patterns, but the relations between these patterns have not until now been analysed sufficiently well. Meanwhile, knowing these relations is exactly what would make it possible to fully understand the process of damaging and especially the interrelation between macro-damaging and micro-damaging.

Among the strength criteria, the conditions triggering the dangerous state at a certain point within the time period under consideration – a topic of the classical theory of failure, are of great importance.

Under a stable strain, the crack remains stationary under the action of constant external loads. Accordingly, for the crack to start developing such loads have to increase, that is, under the effect of changing external factors the damage grows and this happens, when the intensity factor reaches its critical value. The start of the crack propagation, i.e. the crossing of the fracturing boundary, is just that additional criterion needed for solving the problem of the limit equilibrium of a solid with a crack.

Due to the fact that the progress of the process is gradual, a plastic zone emerges at the end of the crack – that means that at the onset of the breaking process the forces are not transmitted via it, but with the growth of the stress at the end of the breaking process additional forces arise in the plastic deformation zone.

As a result of the growth and accumulation of such additional forces, the build-up of micro-faults takes place in the plastic deformation zone and these micro-faults are the basis for the development of conditions for the future rupture or crack formation followed by the complete break-up.

Hence, the disintegration of the caryopsis occurs only in case the maximum stress σ caused by mechanical or other effects exceeds the permissible stress σ_1. Thus, in order to avoid the caryopsis breaking, it is necessary to meet the condition $\sigma \leq \sigma_1$.

In those cases, where several cracks of different lengths exist, the greatest threat is constituted by the crack that is the first to start propagating. In all cases, the crack propagation mechanism is uniform and operates with certain fluctuations.

The pattern of caryopses breaking, i.e. to what extent more often and in which plane they break, depends on the propagation of the cracks and how many of them have under the current external load reached the critical length. The direction, in which the crack will propagate, depends in the majority of cases on the direction of the external loads and the biologic state of the caryopsis.

On the basis of the above-mentioned, a conclusion can be made that the strength of caryopses depends on their damaging and rise of cracks in them, while the increase of the latters' sizes causes the caryopses to break, i.e. to sustain macro-damage.

The analysis of the experimental data obtained by the authors makes it obvious that, as the crack's length increases, the force needed to break the caryopsis decreases (Fig. 3. Similarly, the maximum stress needed for breaking, also becomes lower (Fig. 4).

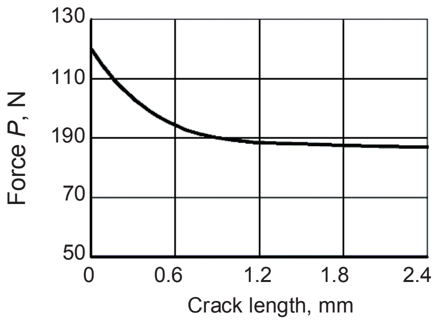

Figure 3. Effect of crack's length on force sufficient for breaking caryopsis.

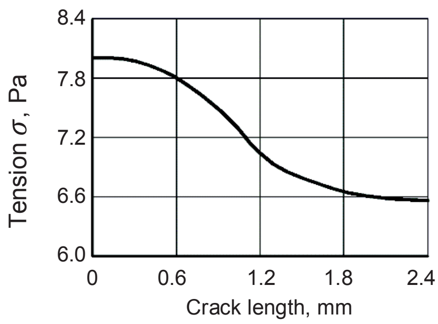

Figure 4. Effect of crack's length on maximum stress.

The authors have also established that the strength of caryopses depends also on the damaging of the germ, endosperm and seed coats, i.e. on the micro-damaging (Table 1).

Table 1. Effect of various types of damaging on strength of caryopsis

Type of damaging	Breaking force P (N)	Breaking deformation ΔL (mm)	Maximum stress σ (Pa)
Knocked-out germ	46.5	0.15	3.46
Damaged endosperm	78.0	0.24	5.79
Damaged germ	84.4	0.22	6.30
Damaged coats of germ and endosperm	95.3	0.22	7.08
Damaged coat of endosperm	103.6	0.22	7.69
Damaged coat of germ	104.5	0.22	7.70
No damage after threshing	108.3	0.22	8.07
Variation factor %	14.2	9.6	12.8

The analysis of the data presented in Table 1 proves that the caryopses, in which the cracks have propagated to a depth of 0.25–0.75 of the endosperm size or deeper, have significantly lower strength in comparison with those free from such damage.

Table 1 shows that the strength of caryopses is affected by the applied forces that damage the germ, endosperm and coats.

The extent of any variations in the parameters being studied in Table 1 was acceptable, ie. classed as being at medium, as evidenced by the variation coefficient not exceeding 14.2%.

The maximum stress has effect on the growth of deformations, damaging and breaking, i.e. the micro- and macro-damaging of caryopses.

Hence, the greater loading the caryopses suffer in the course of the work processes, the lower their strength becomes and the greater possibility of their damaging arises.

During the theoretical, field and experimental research into the effect the tools in the threshing machines of combine grain harvesters have on the damaging and quality of caryopses, it was established that the primary areas, where the greatest damaging and breaking was sustained by the caryopses, were situated at the points, where the grain flow velocity vector changes sharply. In view of the fact that the vector can change in terms of both its magnitude and direction, the area of the greatest damaging is located in the first half of the threshing process.

Comparing the makeup of the first half of the threshing process in drum and rotor threshing machines, it becomes obvious that this leg of the process is considerably more ‘economical’ in rotor threshers and that results in significantly lower caryopsis damaging and breaking rates in them, as compared to the drum machines.

The damaging of caryopses results from the impact impulse, which can be determined with the use of the impulse-momentum theorem for the case of impact interaction written in the vector form (Derevyanko, 2015):

$$m\overline{V}_2 - m\overline{V}_1 = \overline{S}(t) \, , \tag{2}$$

where $\bar{S}(t) = \int_{t_1}^{t_2} \bar{F}\,(t)dt$ – impact impulse; $\bar{V}_1$ and $\bar{V}_2$ – velocity vectors of the grain heap element before its interaction with the beaters in the threshing machine and after passing them, respectively.

The Eq. (2) in terms of its projections on the Cartesian axes appears as follows:

$$\left.\begin{aligned} mV_{2x} - mV_{1x} = S_x(t)\,, \\ mV_{2y} - mV_{1y} = S_y(t)\,. \end{aligned}\right\} \tag{3}$$

By using the above-mentioned theorem, from the Eqs (3) the authors have derived analytically the ratio P between the impact impulses generated in the first half of the threshing process by the drum apparatus and the similar impact impulses in the rotor thresher, which has the following form:

$$P = \sqrt{\frac{V_1^2 + V_{ps}^2 + 2V_1V_{ps}\sin\beta}{V_1^2 + \left(V_{ps}\cdot\sin\alpha\right)^2 - 2V_1V_{ps}\sin\alpha\cdot\cos\left(\alpha+\beta\right)}}\,, \tag{4}$$

where β – angle between the velocity vector $\bar{V}_1$ (i.e. the velocity of grain particles before colliding with the beater bar in the drum thresher or with the rotor in the rotary axial threshing and separating machine) before the impact and the horizontal; α – angle between the velocity vector $\bar{V}_2$ and the horizontal; $\bar{V}_{ps}$ – circumferential velocity of rotation of the drum or the rotor; also, $V_2 = V_{ps} \cdot \sin\alpha$

As a result of the subsequent calculations, it has been established that the value of the impact impulse generated, when using drum threshing and separating machines, is considerably higher than that in case of using rotor threshers.

The experimental data for the damage sustained by grain during its threshing in the DON-1500B combine grain harvesters with drum type threshing apparatus and the rotor type threshing and separating apparatus of the John Deere S760 harvesters have been analysed statistically. The analysis of the caryopsis damage rates in relation to the rotation frequencies of the drum and rotor threshing machines presented in Tables 2 and 3 in percentages (i.e. caryopsis micro-damaging and breaking) The said data were obtained as a result of the field experimental investigations carried out in the same conditions by means of threshing with the use of a drum thresher-separator and with the use of a rotor threshing and separating machine and sampling the grain immediately after the threshing. The grain moisture content during the threshing and at the time of sampling was measured with high accuracy and its value was within the range of 13.5–21.5%. The rotation frequencies of the threshing and separating machines in both types of combine grain harvesters were set up at different levels and monitored and recorded in the PC with the use of special sensing elements.

Table 2. Damage inflicted on caryopses by drum threshing apparatus in DON-1500B combine grain harvester

Indicator	Caryopsis damage rate (%)							$\hat{E}$
Drum apparatus revolutions (rpm)	600	700	750	800	820	900	980	-
Broken caryopses	0.79	0.81	1.36	1.44	3.28	4.97	6.14	9.6
Micro-damaged caryopses	26.40	26.86	28.40	31.22	36.60	42.40	52.70	8.8

The extent was negligible of variations in the parameters being studied in Table 2 and Table 3, as evidenced by the variation coefficient not exceeding 10.2%.

Table 3. Damage inflicted on caryopses by rotor threshing apparatus in John Deere S760 combine grain harvester

Indicator	Caryopsis damage rate (%)							$\hat{E}$
Rotor apparatus revolutions (rpm)	600	700	750	800	840	900	980	-
Broken caryopses	0.07	0.17	0.11	0.23	0.75	0.95	2.08	10.2
Micro-damaged caryopses	21.38	24.29	25.07	26.35	28.37	30.12	31.95	9.6

The diagram in Fig. 5 shows the graphic relations between the percentage rates of the caryopses broken by the threshing apparatus of the drum and rotor types and the rotation frequencies of the drum and rotor, respectively.

The graphic relations between the percentage rates of the caryopses micro-damaged by the threshing apparatus of the drum and rotor types and their rotation frequencies are shown in Fig. 6.

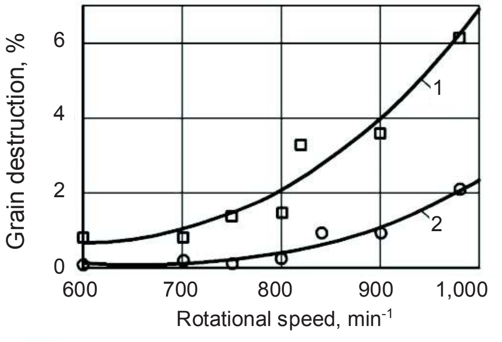

Figure 5. Relation between percentage rate of broken caryopses and frequency of rotation: 1) drum threshing apparatus; 2) rotor threshing apparatus.

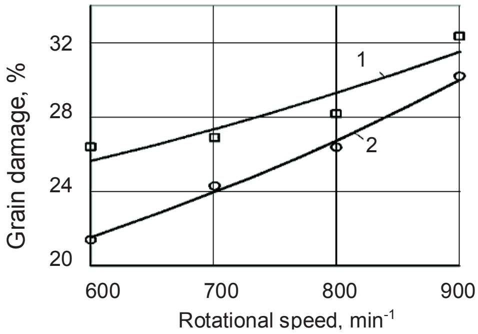

Figure 6. Relation between percentage rate of micro-damaged caryopses and frequency of rotation: 1) drum threshing apparatus; 2) rotor threshing apparatus.

The extensive experimental, field and laboratory investigations of the effect produced by the mechanical loads applied during the work processes from the harvesting to the drilling, which have for several years been carried out in various farm units of the Ukrainian Forest Steppe and Polesye with various cereal crops, give evidence of the substantial difference in the micro-damaging of winter wheat seeds harvested with combine grain harvesters equipped with drum threshing machines, as compared to their harvesting with the use of combine grain harvesters with rotor threshing apparatus (Table 4). For example, in the PP Ukraine in the Zhitomir Oblast, the amount of macro-damaging increases to 6.4% after the threshing in a combine grain harvester equipped with a drum thresher, while in a combine grain harvester with a rotor threshing machine it reaches only 3.1%, which means a more than two-fold difference.

Table 4. Damage sustained by winter wheat seeds during their harvesting with the use of combine grain harvesters with drum and rotor threshing apparatus

Farm unit (wheat variety)	Exami-nation stages	Macro-damage, %	Micro-damage, %				
			Germ		Total damage of bran	Intact	Composit e index of damage
			Knocked out	Damaged			
PP Ukraine,	in header	3.2	2.2	4.0	22.4	77.6	14.91
Zhitomir Oblast	after drum	6.4	4.0	6.2	41.6	58.4	25.52
(Odesskaya – 237)	in hopper	7.8	4.6	7.8	54.0	45.0	31.64
SVK Mayak	in header	2.8	1.8	2.4	17.2	82.2	6.28
Vinnitsa Oblast	after rotor	3.1	2.2	2.8	21.2	79.8	8.24
(Odesskaya – 237)	in hopper	3.9	2.9	3.1	23.0	77.0	9.23
Variation factor %		10.4	8.8	9.6	12.2	11.8	12.4

As is obvious from the data in Table 4, the total amount of the seeds with micro-damage in the hopper of the combine grain harvester equipped with a drum threshing machine is equal to 54.0%, while in the output of the combine grain harvester with a rotor threshing machine they total 23%. These figures indicate an obvious and substantial difference, that is, a two-fold increase, which is due first of all to the modes of operation of the threshing implements under consideration, the difference in their revolution rates, and also to the velocity of the grain heap prior to entering and passing the threshing work process.

It is also worth noticing that the macro- and micro-damaging and cracking take place in organic matter, that is, in a biologically living caryopsis, which implies a considerable effect on the quality factors, on which the yield depends to a significant extent.

The extent of any variations in the parameters being studied in Table 4 was acceptable, ie. they were classed as being at medium, as evidenced by the variation coefficient not exceeding 12.2%.

In the above context, the obtained data can be considered as a convincing proof of the need for the practical application of efficient and high-performance equipment during the harvesting, processing and drilling of the seeds with the aim of ensuring their higher quality, which will provide for obtaining high yield and a considerable growth of the gross output of grain – a fundamental element in the human food supply.

CONCLUSIONS

1. The completed research work has proved that various kinds of macro- and micro-damaging have a substantial impact on the strength of caryopses, in particular, the breaking forces increase more than 2.5 fold, the breaking deformation increases to 0.22 mm, the maximum stress increases more than twofold.

2. The ratio between the impact impulses generated in the first half of the threshing process by drum and rotor machines has been found analytically.

3. The analytical calculations carried out prove that the impact impulse generated in the drum threshing apparatus considerably exceeds the one in the rotor machine, which is supported by the results of the experimental investigations on grain damaging.

4. When the revolution rate of the drum increases from 600 to 980 rpm, the amount of macro-damaged caryopses increases from 26.4% to 52.7%, while the same speed-up of the rotor results in a change from 21.38% to 31.95%.

5. Hence, the theoretical calculations and the obtained graphic relations for the caryopsis micro-damaging and breaking rates support the results of the experimental field research, which indicate that these negative indicators are significantly higher in case of employing drum threshing machines, as compared to the rotor threshers, that is, the damaging and breaking of winter wheat and rye seeds during their harvesting with the use of rotor combine grain harvesters is significantly less intensive, therefore, the quality of seeds is higher.

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