Для оперативного контролю за станом шару зернової купи, що сепарується, при його очищенні від домішок у пневмосепараційному каналі запропоновано використовувати ультразвукові хвилі частотністю 40 кҐц.

Виявлена залежність між наданням повітря та матеріалу від різниці середніх значень довжин шляхів ультразвукових хвиль, отриманих з ультразвукових далекомірів, що встановлені на початку, у середині та вкінці пневмосепараційного каналу.

Ґрунтуючись на цій закономірності, розроблено засіб контролю та забезпечення заданої порозности зернового шару у пневмосепараційному каналі очищувача зернового шару. Спосіб заснований на принципі постійного розрахунку різниці середніх значень довжин шляхів ультразвукових хвиль, отриманих з далекомірів, розташованих у пневмосепараційному каналі. Отримані значення передаються до блоку керування з метою їх обробки шляхом порівняння отриманих значень із заданими. Якщо є відхилення отриманих значень від тих, що задані, проводиться регулювання подачі матеріалу та/або повітря до пневмосепараційного каналу.

Розроблений спосіб оперативного контролю за станом сепаруємого шару дозволяє у процесі очищення підтримувати зернівки у підвішеному стані із заданим рівнем псевдозрідження.

Цим забезпечуються найкращі умови видалення смітних домішок по всьому об'єму зернового шару, висока якість очищення зерна при високій продуктивності очисника

Ключові слова: ультразвук, очищення зерна, пневмосепараційний канал, контроль за порозностю зерна, надання матеріалу, витрата повітря

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DEVELOPMENT OF A TECHNIQUE TO CONTROL AND ENSURE THE PREDEFINED POROSITY OF A GRAIN LAYER IN THE PNEUMO-SEPARATING CHANNEL AT A GRAIN HEAP CLEANER

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1. Introduction

One of the main challenges for agriculture is to increase production of food and fodder grain, in order to have the necessary capacity and resources for export. This necessitates bringing the gross yield of grain to 1 ton per person [1].

An important element of cultivation and grain production is its postharvest handling, which amounts to 40 % of the cost structure. Timely and qualitative post-harvest treatment is an important reserve for increasing grain output [2].

Post-harvest grain treatment involves machinery for preliminary, primary, secondary cleaning and sorting, most of which is equipped with pneumo-separating systems or assembled as stand-alone machines.

A grain heap sent for the post-harvest treatment is a mixture of high-grade, puny and damaged grains (seeds) of the basic crop, seeds of different cultivated and weed plants. In addition, a grain heap contains impurities of organic (particles of plants, straw, wheat straw) and mineral (sand, lumps of soil, etc.) origin. In this case, the content of seeds of the basic crop in a heap varies widely and is 70...98 %.

During treatment, the grain and seed material is brought to the required standards (conditions), which are specified by specialized regulatory and technical state standards.

When separating a grain heap into fractions, the most common technique is to separate grain mixes in a vertical air flow – the pneumo-separating channel (PSC), due to the structural simplicity and compactness of the device.

Typically, PSC operate as part of production lines. A material for treatment received from harvesters has a heterogeneous structure, its properties change stochastically. Over 24 hours, the moisture content of a heap may range from 14 to 35 %, and the impurity content – from 5 to 30 % [3]. A change in the properties of the treated material over time inevitably leads to a change in all variables of the process state. A change in the properties of the treated material when it is sent to PSC causes a change in the aerodynamic drag of the system and in the air speed inside the layer of the treated material. When air speed significantly exceeds the optimal this results in that particles of the basic crop are discharged into waste, while reducing this speed compromises the quality of cleaning. The operation of a production line may also be accompanied with fluctuations in the supply of the cleaned material to PSC; increasing the amount of a material entering PSC increases the thickness of the blown layer, which reduces cleaning efficiency. A low feed leads to poor performance. At PSC operation, the main task is to maintain the optimal supply of air and a material into the zone of separation.

Most grain cleaning machines are supplied with air and a material to PSC manually by operator [3]. However, given the stochastic change in a material flow's properties, an operator is not able to timely respond to air pulsation and to changes in the properties of a material during a production line operation.

To reduce labor costs related to control, manufacturers have started to apply different systems to maintain air speed in PSC [4]. Their main drawback is the lack of possibilities to regulate the supply of air into a layer when the layer structure of the treated material changes, which significantly affects separation quality of a multi-component mixture.

The lack of a means to operatively control the state of the separated layer in PSC and to maintain its condition inevitably leads to poorer performance of the cleaner and lower effectiveness of grain mixes cleaning.

2. Literature review and problem statement

Despite the emergence, in recent years, of separators that employ new principles, pneumatic separators are still widely popular. Paper [5] reports results of research into the pneumoseparation of flour, it shows the influence of various factors on the process of separation. Study [6] gives a model to determine the motion trajectory of small separated particles, which was tested in practice. However, both cited papers have not resolved tasks associated with the operative control over the state of a grain layer. Important at pneumo-separation is the difference between the aerodynamic characteristics of separated impurities. Study [7] reports results of research into determining the critical air velocity, the drag coefficient, and a Reynolds number for separating pomegranate seeds. Work [8] identified the factors influencing the progress of pneumo-separation of lupine seeds. The results obtained in both studies are used to improve the performance and quality of pneumoseparation, however, the supply of a material and air to PSC is configured manually. This is the approach for setting the supply of air and the separated material to PSC that was used in common German Petkus grain cleaning machines [9], as well as separators Oliver [10]. In the specified grain cleaning machines, configuring the air velocity and the supply of a material to PSC is carried out manually by using gate valves. An option for reducing labor costs related to control could be the automated maintenance of air speed in PSC, employed in the grain cleaning machines Vestrap [4]. In these machines, air speed is set at a remote control and is maintained constant automatically. However, the disadvantage of this control technique is impossibility to adjust air supply at a change in the structure of a treated material's layer, which significantly affects separation quality of a multi-component mixture.

Operative control over the state of a separated layer has been advanced in a variety of ways. Traditional mechanical cleaning methods are currently complemented by the capacity of computing machines that employ artificial intelligence, for example, configuring photo-separators involves machine learning [11]. Paper [12] proposed using genetic algorithms when setting optimal parameters for buckwheat seed separation. However, results from above studies have not been practically applied. The reason for this is probably the lack of knowledge and low efficiency of these systems.

Of particular importance to ensure the specified state of a grain layer is the use of sensors to monitor the separation, especially for the case when these sensors operate in real-time and the data they provide are used to operatively control the technological process. Chemical analysis of grain in real-time involved cheap sensors, which operate on the basis of spectral analysis. Such sensors have been designed for grain separators [13], as well as to analyze a grain heap from a harvester [14]. However, still unresolved are the tasks associated with using such sensors to operate PSC.

Control systems to manage bed grains porosity are applied in the coal mining industry at hydraulic sedimentation machines when enriching useful minerals [15]. These systems employ pivoting float-type sensors, which are, via a strap, attached to the movable bracket's axis and are installed at a certain height above the sieve. The angular position sensor itself is attached to the float's strap. The sensitive element used is the integrated micromechanical accelerometer. Electronic circuitry of the sensor enables the adjustment of a gain factor, a filter cutoff frequency, the adjustment of «zero». The angular position sensor converts an inclination angle into a current signal of 4–20 mA [16]. The system executes automatic control and management of water and air flow supply into the machine. Such sensors cannot be used in pneumatic separators because of the high float windage, resulting in additional drag of the system and an uneven airflow distribution. It is not possible to control the supply of a material to PSC mesh by such a sensor because the float would mostly respond to the air flow pulsations.

One technique to monitor and maintain the predefined grain porosity in PSC is to use ultrasound (US) range finders. This is the approach used in the current work. According to a given technique, adjustment of air supply into grain is carried out based on comparing the length of a US wave path that passed the grain layer to a certain value set by the operator in advance. The disadvantages of this technique include the fact that a US wave penetrates the layer in the direction of its movement. For this reason, qualitative assessment of the internal structure of a grain layer with changing physical and mechanical properties in the process of its cleaning is impossible.

To date, there are neither techniques nor devices to execute operative control over the state of a moving grain layer at its cleaning. All this allows us to argue on the appropriateness of undertaking a study into the development of a technique and a device to estimate and maintain the predefined layer porosity in PSC by using ultrasound.

3. The aim and objectives of the study

The aim of this study is to develop a technique and a device to operatively control, and maintain in the predefined state, a moving grain layer by using ultrasound.

To accomplish the aim, the following tasks have been set:

– to substantiate the technique to control and ensure the predefined porosity of a grain heap layer in the process of its cleaning;

– to define the operational parameters for the designed device to control and ensure the predefined porosity at which performance and quality of work of a pneumo-separating channel meet the requirements to machines for primary cleaning of grain heap.

4. Materials and methods to study a technique to control and ensure the predefined porosity of a grain heap in a pneumo-separating channel

To elucidate the concept [17], we shall consider the motion of a US wave through a grain heap layer (Fig. 1).

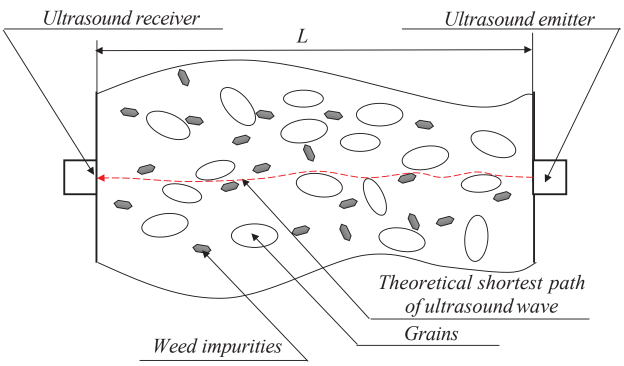

Fig. 1. The US wave path that passes a grain heap layer

The US wave path, L_3, mm, passing through a grain heap layer, taking into consideration diffraction, can be determined from the following dependence [18]:

$$L_3 = L - d_e \cdot n + \frac{l_e \cdot k}{2} \cdot n, \qquad (1)$$

where L is the distance from the emitter to the receiver, mm; d_e is the equivalent diameter of a material's particle, mm; n is the sum of particles of grain heap along a US wave path; k is an empirical factor depending on the length of a US wave and the shape of a material's particles; l_e is the equivalent length of a particle's circumference, mm.

The proposed technique to control and maintain the predefined porosity of a grain layer is implemented at an installation for cleaning grain heap (Fig. 2).

The developed scheme for the system to control and ensure the predefined porosity of a grain layer in PSC is shown in Fig. 3.

The system includes:

– three US range finders along the perforated mesh at the beginning, in the middle, and at the end of PSC to control the porosity of a treated material's layer;

– frequency converters to control electric motors of the fan and the feed roller;

– a microcontroller unit of system control.

The principle of operation of range finders is based on measuring the time it takes for a sound wave to travel from the emitter to the receiver.

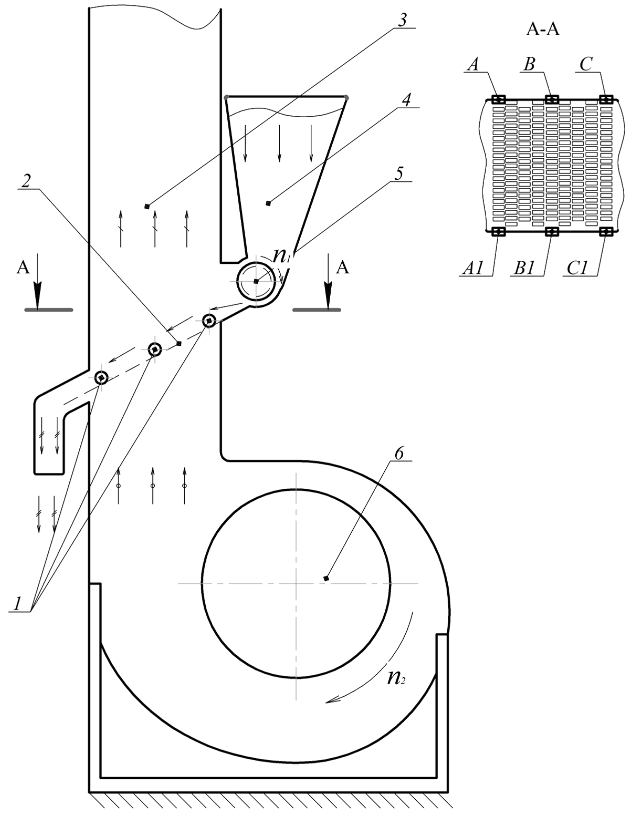

Fig. 2. Technological diagram of a pneumo-separating channel, equipped with ultrasonic range finders: — grain heap; — air flow with light impurities; — air flow; — cleaned grain; n_1 — rotation speed of a feed roller; n_2 — fan rotation speed; A, B, C — US emitters; $A1$, $B1$, $C1$ — US receivers; 1 — US range finders; 2 — perforated mesh; 3 — pneumo-separating channel; 4 — feed hopper; 5 — feed roller; 6 — fan

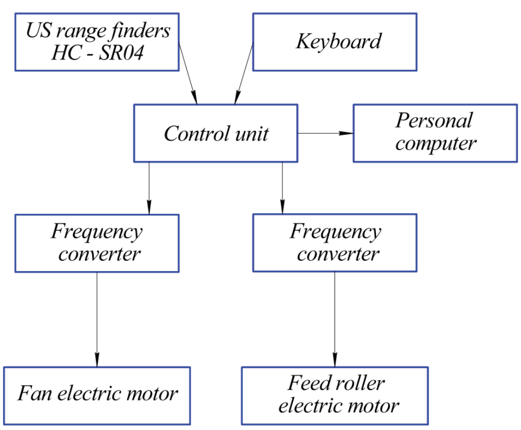

Fig. 3. Scheme of the system to control and ensure the predefined porosity of a grain layer in PSC

The operational process of cleaning a grain heap from impurities proceeds as follows. The bulk of grain from a harvester is sent to feed hopper 4 (Fig. 2). From the hopper, using feed roller 5, the bulk of grain is sent to PSC 3 onto perforated mesh 2; it is exposed to the airflow generated by fan 6. When grain moves along the perforated mesh, its fluidization occurs along with cleaning from light impurities; the inner structure of the blown layer changes.

The state of the fluidized layer is operatively registered by ultrasonic range finders 1 (Fig. 2). The US waves with a frequency of 40 kHz are radiated at intervals of 150...1,500 ms by emitters *A, B, C* and pass, at a speed of about 340 m/s, through a layer of the treated material moving at a speed of 0.1...0.4 m/s across its movement to receivers *A*1, *B*1, *C*1. Values for the lengths of ultrasonic waves paths, acquired from US range finders, located at the beginning (L_{1av}), in the middle (L_{2av}), and at the end (L_{3av}) of PSC, are sent for processing to the microcontroller control unit where their average values are computed.

The designed PSC, equipped with a system to control and ensure the predefined porosity of a grain layer, was installed at the production line between a receiving compartment for drying and ventilating a grain heap and the feed hopper.

The PSC was set to operating mode manually. The system to control and ensure the predefined porosity of a grain layer was enabled by the operator by pressing the button at the control unit. In this case, the system determined differences between the average values for lengths of US wave paths, acquired from the US range finders, located at the beginning and end of PSC (L_{1av}–L_{3av}), in the middle and end of PSC (L_{2av}–L_{3av}) over a certain period. These values were recorded by the software as operational (predefined) ΔL_P and ΔL_B, respectively. The system constantly computed L_{1av}–L_{3av} and L_{2av}–L_{3av}. Assuming that a material to be cleaned has a heterogeneous structure, it contains impurities of organic and inorganic origin of varying moisture content and density, shape and size. In this regard, L_{1av}–L_{3av} and L_{2av}–L_{3av} are within a wide range and they deviate from the predefined values. When detecting the deviations L_{1av}–L_{3av} and L_{2av}–L_{3av} from the predefined ΔL_S and ΔL_A, the system adjusted the supply of a material and/or air to PSC until L_{1av}–L_{3av} and L_{2av}–L_{3av} return to the predefined range (2), (3):

– to control the feed roller rotation frequency:

$$(L_{1av}-L_{3av})X_1 \le \Delta L_S \le (L_{1av}-L_{3av})X_2, \qquad (2)$$

where X_1, X_2 are the magnitudes that determine, respectively, the lower and upper bounds of the variation interval for L_{1av}–L_{3av} and L_{2av}–L_{3av}, being within which there was no action applied to the working bodies of PSC.

– to control the fan rotation frequency:

$$(L_{2av}-L_{3av})X_1 \le \Delta L_A \le (L_{2av}-L_{3av})X_2. \qquad (3)$$

Subject to conditions (2) and (3), the mode of PSC operation is working.

When modelling the process of treating a material in the designed PSC (Fig. 4), the following indicators were accepted as basic varied factors:

– supply of a material to PSC, Q_m, kg/h;

– air flow rate in PSC, Q_a, m^3/s.

The output magnitudes (responses) were:

– difference between the average values for lengths of the US waves paths, acquired from the range finders, located at the beginning and end of PSC – L_{1av}–L_{3av}, mm;

– difference between the average values for lengths of the US waves paths, acquired from the range finders, located in the middle and end of PSC – L_{2av}–L_{3av}, mm;

– performance of a pneumatic separator, G, kg/h;

– the amount of impurities in a material at the outlet from PSC, E_i, %;

– completeness of separating the impurities, E_C, %;

– the amount of basic material in the sedimentation chamber, E_h, %, which was determined from formula:

$$E_h = \frac{m_b \cdot 100}{m_3}, \qquad (4)$$

where m_b is the mass of a separated impurity, g; m_3 is the batch mass, g.

Controlled factors are: the initial impurity degree of a treated material, E_{ini}, atmospheric air pressure P_{atm}, the ambient air temperature t, the initial moisture content of a treated material W_{ini}.

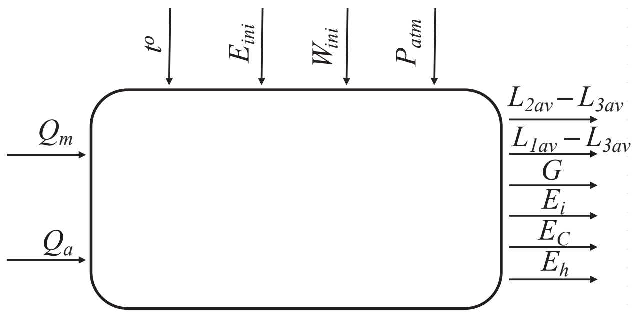

Fig. 4. Modelling the process of material treatment in PSC

The ranges for L_{1av}–L_{3av} and L_{2av}–L_{3av} at which there was no action applied to the working bodies of PSC were calculated based on dependences (2), (3) in accordance with the following scheme; they were subsequently entered to the software of the control unit (Fig. 3).

Experiment No. 1: $X_1=0.97$; $X_2=1.03$;

Experiment No. 2: $X_1=0.95$; $X_2=1.05$;

Experiment No. 3: $X_1=0.93$; $X_2=1.07$;

Experiment No. 4: $X_1=0.90$; $X_2=1.10$.

The control unit was encoded using a personal computer with the installed software Embedded Workbench 6.0 (IAR Systems, Sweden) and a programmer connected to the control unit.

To establish a dependence of change in the periodicity of calling the range finders on the quality of assessing the porosity of a grain heap layer, the experiments involved a correlation analysis (Table 2). To this end, we used a sample of 350...600 values from each number series acquired from US range finders 1 (Fig. 2). The time to check readings from each rangefinder was 150; 450; 750; 1,050; 1,200; and 1,500 ms.

5. Results of research into the application of a system to control and ensure the predefined porosity of a grain layer in a pneumo-separating channel

Our correlational analysis has revealed the presence of correlation between the supply of air and a material on difference between the average values for lengths of the US waves paths acquired from the US range finders installed in PSC (Table 1).

Table 1

Correlation between the supply of air, a material, and differences in the average values for lengths of the US waves paths

Indicator title	Correlation coefficient magnitude of the influence of supplying air and a material on the difference in the average values for lengths of the US waves paths that penetrate the transversely moving grain layer		
	acquired from the US range finders, located at the beginning and end of PSC (L_{1av}–L_{3av})	acquired from the US range finders, located at the beginning and in the middle of PSC (L_{1av}–L_{2av})	acquired from the US range finders, located in the middle and end of PSC (L_{2av}–L_{3av})
Rotation frequency of feed roller, n_1, which controls the supply of s material, Q_m, t/h	–0.89	–0.49	–0.59
Rotation frequency of fan rotor, n_2, which controls air supply, Q_a, m^3/s	–0.18	0.57	–0.82

It is clear (Table 1) that it is possible to regulate the supply of a material based on L_{1av}–L_{3av} – by the rotation frequency of the feed roller's motor, and based on L_{2av}–L_{3av} – to regulate the air supply by the rotation frequency of the fan's motor using frequency converters.

In order to determine the optimal number of values for lengths of the US waves paths acquired from the US range finders, which were used to calculate the average values for lengths of the US waves paths, we analyzed the data stream acquired from US range finders 1 (Fig. 2).

Our analysis of variance in the magnitudes of average values for lengths of the US waves paths acquired from the range finders, located at the beginning, in the middle and at the end of PSC, has revealed that the variance for the sample of average values for lengths of the US waves paths acquired from the US rangefinder, located at the beginning of PSC (L_{1av}) is 37,453.7 mm^2; in the middle of PSC (L_{2av}) is 6,663.4 mm^2; at the end of PSC (L_{3av}) is 2,203.2 mm^2.

A maximum variance in the average values for lengths of the US waves paths is observed in a sample acquired from the rangefinder installed at the beginning of PSC. As the cleaning of a grain heap progresses, its homogeneity increases due to the removal of weed impurities and the uniformity of grain layer fluidization.

The system must be configured so that the calculation of magnitudes of average values for lengths of the US waves paths acquired from US range finders should be conducted based on a sample including not less than 50 values, n_p.

The results from a correlation analysis to establish a dependence of change in the periodicity of frequency of checking readings from range finders on the quality of assessing the stochastic structure of the cleaned layer of a grain heap are given in Table 2.

Table 2

Dependence of change in the periodicity of frequency of checking readings from range finders on the quality of assessing the stochastic structure of the cleaned layer of a grain heap

Indicator title	Magnitude of correlation coefficient at the frequency of checking readings, T_o, ms					
	150	450	750	1,050	1,200	1,500
Influence of a material feed on difference in the average values for lengths of ultrasonic waves paths that penetrate a transversely moving grain layer L_{1av}–L_{3av} (by modulo)	0.89	0.84	0.84	0.89	0.93	0.84
Influence of air flow rate on difference in the average values for lengths of ultrasonic waves paths that penetrate a transversely moving grain layer L_{2av}–L_{3av} (by modulo)	0.82	0.84	0.81	0.80	0.95	0.62

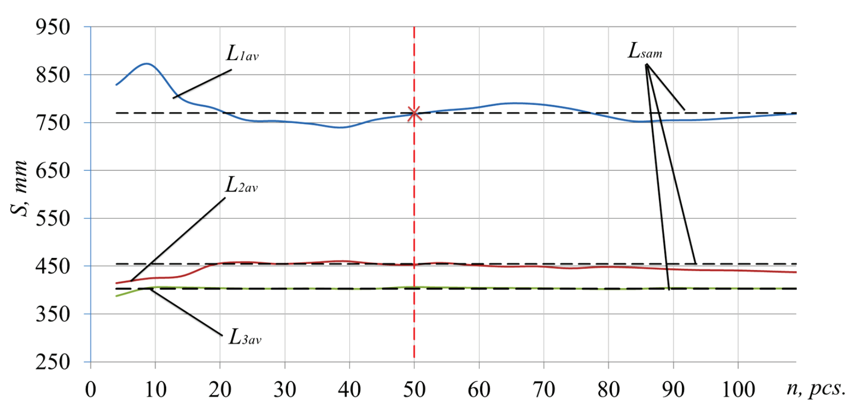

Fig. 5. Change in the magnitude of the average value for paths lengths S, the US waves acquired from the US range finders, located in the beginning, L_{1av}, in the middle, L_{2av}, and at the end, L_{3av}, of PSC, depending on the number of values for n based on which the calculation was performed; L_{1av}, L_{2av}, L_{3av} are the magnitudes of average values for lengths of the US waves paths acquired from the US range finders, located at the beginning, in the middle, and at the end of PSC, respectively; L_{sam} are the magnitudes of average values for lengths of the US waves paths acquired from the US range finders, located at the beginning, in the middle of PSC, calculated across a full sample

When the frequency of checking readings of range finders equals 1,200 ms, the correlation coefficients of the influence of air and a material feed on L_{1av}–L_{3av} and L_{2av}–L_{3av} are maximal; the quality evaluation of porosity of the grain heap layer is high.

The system to control and ensure the predefined porosity of a grain layer activates the working bodies at frequency that can be defined from dependence:

$$T_i = T_p \cdot n_y, \quad (5)$$

where T_i is the period over which the system to control and ensure the predefined porosity of a grain layer acts on the working bodies of PSC, ms; T_p is the frequency of checking readings from the US range finders, ms; n_v is the number of values from the US range finders that are used to calculate the magnitudes for average value for lengths of the US waves paths acquired from US range finders.

Since correlation coefficients accept high values, exceeding 0.8 (except for T_p=1,500 ms), over all periods of checking the readings, in order to accelerate responsiveness of the system to changing porosity, one should accept T_p=150 ms.

The result of our experimental study is the defined ranges for L_{1av}–L_{3av} and L_{2av}–L_{3av} over which the working bodies of PSC are not activated (Fig. 6).

The results from experimental research into determining the operational parameters for the designed device with a system to control and ensure the predefined porosity of a grain layer in PSC are given in Table 3.

The system to control and ensure the predefined porosity of a grain layer, when setting the values X_1=0.95; X_2=1.05, enables the PSC operation that meets quality requirements to work of machines for primary grain cleaning (Table 3). At these parameters, one observed the maximum performance of PSC – 2,002.50 kg/h, amount of impurities when exiting PSC is 0.29 %, the amount of basic material in the sedimentation chamber is 0.32 %. In this case, completeness of weed plant separation is 91.05 %. At primary cleaning, the losses of quality grain should not exceed 1.5 % in forage waste and 0.05 % in impurities, crushing – not larger than 1 %, the completeness of weed impurity separation – not lower than 60 % [19].

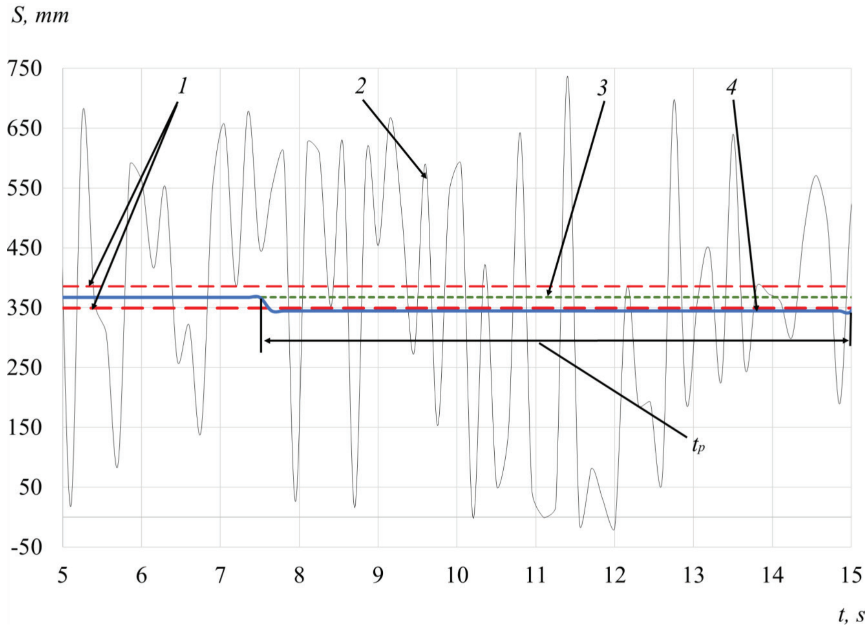

Fig. 6. Implementing the process of software-based calculation of difference in the average values for lengths of the US waves paths L_{1av}–L_{3av} acquired in the course of experimental study from range finders at X_1=0.95; X_2=1.05: 1 – range for L_{1av}–L_{3av} over which the working bodies of PSC are not activated; 2 – difference in the values for lengths of the US waves paths acquired from the range finders located at the beginning and end of PSC (L_{1av}–L_{3av}); 3 – preset difference in the average values for lengths of the US waves paths acquired from the range finders located at the beginning and end of PSC (ΔL_S); 4 – magnitudes of average values for lengths of the US waves paths acquired from the US range finders, calculated based on 50 values; t_p is the period of calculating the difference in average values for lengths of the US waves paths acquired from the range finders located at the beginning and end of PSC (L_{1av}–L_{3av}), calculated based on 50 values

Table 3

Performance and operational quality of PSC at different operational parameters for the designed device to control and ensure the predefined porosity of a grain layer

Operational parameters for the device to control cleaning process	Pneumatic separator performance, G, kg/h	Initial content of impurities in treated material, E_{ini}, %	Amount of impurities in material when exiting PSC, E_i, %	Amount of basic material in sedimentation chamber, E_h, %	Completeness of impurities separation, E_C, %
Experiment No. 1: X_1=0.97; X_2=1.03;	756.00	5.97	0.62	2.02	95.10
Experiment No. 2: X_1=0.95; X_2=1.05;	2,002.50	3.48	0.29	0.32	91.05
Experiment No. 3: X_1=0.93; X_2=1.07;	1,512.00	2.05	0.49	0.14	68.57
Experiment No. 4: X_1=0.90; X_2=1.10	1,192.50	4.59	0.45	0.54	89.57

Results from our analysis of variance in the operation of the system to control and ensure the predefined porosity of a grain layer in PSC are given in Table 4.

Table 4

Results from a variance analysis of difference in the values for lengths of the US waves paths acquired from the range finders installed in PSC

Operational parameters for the device to control the process of cleaning	Value of variance in numeric series L_{1av}–L_{3av}	Value of variance in numeric series L_{2cp}–L_{3cp}
Experiment No. 1: X_1=0.97; X_2=1.03;	91,401.75	15,855.25
Experiment No. 2: X_1=0.95; X_2=1.05;	40,875.94	4,647.88
Experiment No. 3: X_1=0.93; X_2=1.07;	72,223.11	4,084.34
Experiment No. 4: X_1=0.90; X_2=1.10	95,954.06	30,411.53

It follows from Table 4 that the system works most efficiently at X_1=0.95; X_2=1.05. Under this mode, one observes the smallest deviations from the average values of numeric series L_{1av}–L_{3av} and L_{2av}–L_{3av}, which also confirms the effectiveness of a given regime.

6. Discussion of results of studying the technique to control and ensure the predefined porosity of a grain layer in a pneumo-separating channel

Application of the devised technique to control and ensure the predefined porosity of a grain layer based on US in PSC would make it possible to perform the high-quality cleaning of a grain heap with changing physical and mechanical properties of the grain flow (Table 3). This is achieved due to that the propagation speed of US waves (Fig. 2) through a grain layer is much higher, by 850...3,400 times, than the movement speed of individual grains within a fluidized layer. Range finders are very sensitive to changes in the structure of a layer. In particular, during cleaning, at the beginning of PSC the average value based on the sample of the path a US wave traveled is 768 mm (Fig. 5) with a variance of 37,453.7 mm^2. This can be explained by a higher density of the grain layer and its high weed contamination in the beginning of cleaning. In the end of the cleaning, the average value for a US wave path is 403 mm with a much smaller variance of 2,203.2 mm^2, owing to the uniformity of grain distribution throughout the layer's volume and its homogeneity.

A frequency of checking readings from the range finders of 150 ms ensures a timely response from the system to control and ensure the predefined porosity of a grain layer (Fig. 6) to a change in the level of fluidization of a grain heap flow. The system's operating principle makes it possible to independently control the air flow rate and the supply of a material to PSC (Fig. 3, 4).

The disadvantages of the devised technique are in that its application for grain cleaning machines would require using sophisticated equipment; handling it would require highly skilled staff.

The derived analytical expressions (2), (3) make it possible to program the microcontroller and monitor the grain cleaning process, to improve effectiveness of the cleaning process in general.

Results from the current study could be used for PSC at grain cleaning machines where a treated material resides on a sloping mesh. In this case, existing control systems need minimal modification. The system to control and ensure the predefined porosity of a grain layer in PSC could run as a standalone device, whose remote sensors and control unit are easily included in any structural and electrical circuits of a grain cleaning machine.

The results reported here are continuation of the authentic work in the development of a complex technological process related to post-harvesting grain treatment [20]. In the future, it is possible to apply findings from the current study to automate the cleaning process in vertical PSC where grain movement inside PSC is driven by gravity.

7. Conclusions

1. We have devised a technique to control and ensure the predefined fluidization of a grain layer in PSC based on the character of change in the porosity of a grain heap layer in the process of cleaning it. Our study has shown that a material feed can be set and controlled based on difference in the average values for lengths of the US waves paths that penetrate a transversely moving grain layer, acquired from the US range finders installed at the beginning and end of PSC. It is possible to set and control air supply based on difference in the average values for lengths of the US waves paths that penetrate a transversely moving grain layer, acquired from the US range finders installed in the middle and end of PSC.

2. We have defined rational operational parameters for the designed device to control and ensure the predefined porosity of a grain layer at the PSC of a cleaner. A frequency of checking readings from the US range finders is 150 ms; a sample to calculate difference in the average values for lengths of the US waves paths contains 50 values. The bounds of a variation interval in the difference between average values for lengths of the US waves paths is ±5 % from the predefined values. These parameters enable quality of cleaning a grain heap with the stochastic change of physical-mechanical properties that meets the requirements to machines for primary cleaning of a grain heap. The amount of impurities in grain exiting PSC does not exceed 0.29 %, the amount of a basic material in the sedimentation chamber does not exceed 0.32 %, completeness of weed impurities separation is 91.05 %.

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