ENGINEERING MANAGEMENT OF TWO-PHASE COULTER SYSTEMS OF SEEDING MACHINES FOR IMPLEMENTING PRECISION FARMING TECHNOLOGIES
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ІНЖЕНЕРНИЙ МЕНЕДЖМЕНТ ДВОФАЗНИХ СОШНИКОВИХ СИСТЕМ ПОСІВНИХ МАШИН ДЛЯ ТЕХНОЛОГІЙ ТОЧНОГО ЗЕМЛЕРОБСТВА

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ABSTRACT

The paper covers process flowsheets and design implementation of two-phase coulter systems of seeding machines for precision farming technologies. A mathematical model of the movement of a two-phase coulter system has been developed and simulation modelling has been conducted. As a result, the ability of a two-phase coulter system to operate a specified working mode, if such operating parameters as, for example, the amplitude and the frequency of irregularities entering a coulter system, the mass of a slot cutter and an indenting disk, a damping coefficient, an amplification coefficient etc. are changed, given that there are systematic and random errors of measuring and control elements, has been determined. Technology evaluation of a two-phase coulter system operation was conducted in the field environment by determining the variation coefficients of a seeding depth, the distance between plants in a row, field germination capacity and the average soil consistency in the area of a plant location. Technical and economic assessment of the application of a two-phase coulter system on row-crop seeding machines has been conducted.

РЕЗЮМЕ

В статті відображено технологічні схеми та конструктивну реалізацію двофазних сошникових систем посівних машин для технологій точного землеробства. Побудовано математичну модель руху двофазної сошникової системи та проведено імітаційне моделювання, що дало змогу визначити можливість двофазної сошникової системи виконувати заданий режим роботи при зміні таких параметрів функціонування, як, наприклад, амплітуда і частота надходження нерівностей до сошникової системи, маса щілиноутворювача та вдавлюючого дисків, коефіцієнт затухання, коефіцієнт підсилення тощо, при наявності систематичних та випадкових похибок вимірювальних та контролюючих елементів. Технологічну оцінку робити двофазної сошникової системи проводили в польових умовах шляхом визначення коефіцієнтів варіації глибини заробки насіння, відстані між рослинами в рядку, польової схожості насіння та середньої щільності ґрунту в зоні розміщення насіння. Виконано техніко-економічну оцінку застосування двофазних сошникових систем на просапних сівалках.

INTRODUCTION

Together with soil preparation and crop tending, one of the main conditions for obtaining high yields of tilled crops is the distribution of crop seeds according to agronomical requirements *(Vlăduţ D.I. et al., 2018)*. It contributes to the provision of plants with the necessary amount of light, moist, heat and nutrients *(Aliev E.B. et. al., 2018).*

A change in soil resistance and irregularities in the soil surface while a seeding machine is in operation cause coulter oscillations in a longitudinal-vertical plane, which results in its unstable motion at the selected depth *(Rogovskii I.L. et. al., 2019).* If there is an increase in the movement speed of a seeding machine, the amplitude of coulter oscillations, in a longitudinal-vertical plane, increases as well, which results in greater non-uniformity of seeding depth *(Kotov B.I. et. al., 2019).*

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The existing designs of coulter systems of seeding machines do not provide the sufficient accuracy of distributing tilled crop seeds in the soil *(Bulgakov V. et. al., 2018).*

In the course of solving the problem of the improvement of sowing quality level, a high quality tilled crop sowing achievement hypothesis was made, according to which, in order to improve the quality level of tilled crop sowing, it is necessary to apply a two-phase way of seed covering *(Dinesh J., 2009).*

If such a way of sowing is used, the process of seed covering is performed in two phases *(Kanehl P., 2010)* and each phase includes two stages (Fig. 1).

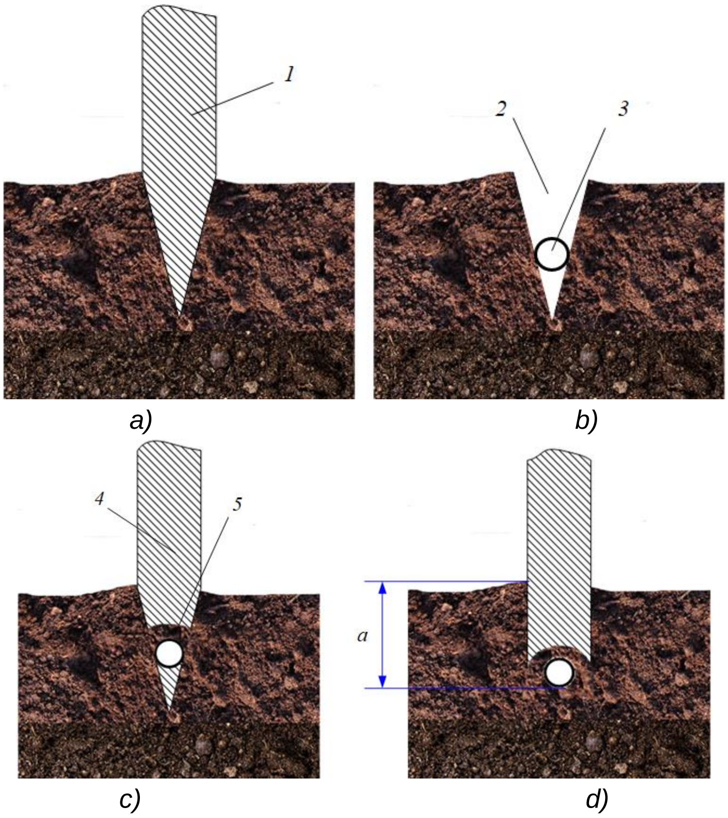

Fig. 1 - The main stages of two-phase seed covering

a, b – the first phase; c, d – the second phase of seed covering

1 – slot cutting disk; 2 – slot; 3 – seed; 4 – indenting disk; 5 – working edges of indenting disk; α – seeding depth

The cycle of the four stages *(Komiwes V. et. al., 2006)* of implementing the suggested method is the following:

▪ the first stage: the slot cutting disk cutter 1 penetrates the soil and makes slot 2 with favourable geometrical parameters for seed self-blocking between the side walls of a slot without its rolling along a row *(Bulgakov V et. al., 2017)*;

▪ the second stage: seed 3 is loaded in slot 2 and, depending on the seed size, it is blocked at various depths (however, it is shallower than the target one) and is arranged along the slot axis *(Asejeva A. et. al., 2013)*;

▪ the third stage: the indenting disk 4 of certain geometrical parameters moves along a slot and cuts wet side walls of the soil by means of its working edges 5; due to the form of the disk groove, during cutting the soil moves down and covers the seed that is located in the slot and, simultaneously, it compacts around it *(Croitoru Şt. et. al., 2017)*;

▪ the fourth stage: the indenting disk 4 moves the seed together with the compacted soil to the target seeding depth a; slot covering is performed in a traditional way *(Aksenov A.G., 2018)*.

Such a two-phase way of tilled crop sowing makes it possible to provide seed covering 1 (Fig. 2) in a wet soil layer 4. The nucleus 2 of moistened soil that is compacted to 1.3 g/cm^3 *(Nilesh N.J. et al., 2015)* is formed around the seed and a fine structure 3 can be formed above. The seed is covered at the target depth (with permissible variation) a irrespective of the state of irregularities and soil density *(Rohokale A.B. et. al., 2014)*. In addition, the uniformity of seed distribution along a row, which is provided by a seeding machine, is not violated and the deviation of seed placement relative to a row centre line is reduced to a minimum *(Shen Qiang et. al., 2015)*.

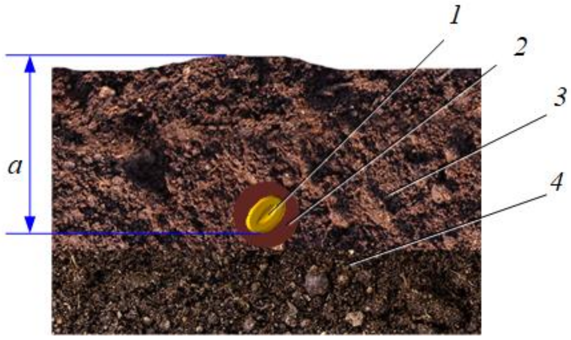

Fig. 2 - Image of a seed covered in the soil

1 – seed; 2 – nucleus of compacted and moistened soil; 3 – fine structure; 4 – wet soil layer; a – seeding depth

The purpose of research is to improve the quality of planting row crops in modern farming technologies by studying the parameters of two-phase coulter systems of seeding machines.

MATERIALS AND METHODS

In order to implement the suggested two-phase method of covering tilled crop seeds, a corresponding design of a coulter system has been developed. It has been determined that, when a disk deepens into the soil, the resistance force of the soil is the influencing factor for the running depth of the indenting disk and it depends on the type of soil and its physical and mechanical characteristics etc. Here, the values of the above stated characteristics are changed to a considerable extent over the field area depending on the coordinates of a seeding unit in the field. It means that it is necessary to take into account the position-determined soil characteristics, namely, its position-determined consistency.

In the further analysis of a coulter system, position-determined information about soil consistency with the possibility of automated correction of an indenting disk position (Fig. 3) is taken into account, which should be able to provide the effective operation of a correction device and a coulter system as a whole within a wide range of operating conditions.

The position of a slot cutter is controlled by a position sensor *D* and its signal is applied to an adder unit *S*. A manual adjustment signal $U_з$ is applied to an adder unit as well. A signal *λ(t)* is obtained at the output and it is sent to the control module of a servo-drive unit. A feedback control signal *Ž(t)* from the position sensor of an indenting disk and the signal *R(x,y)* from the unit of calculation of position-determined soil consistency are sent to this module as well. The later one operates based on the information about the current coordinated of a seeding unit in the field and a position-determined soil consistency map.

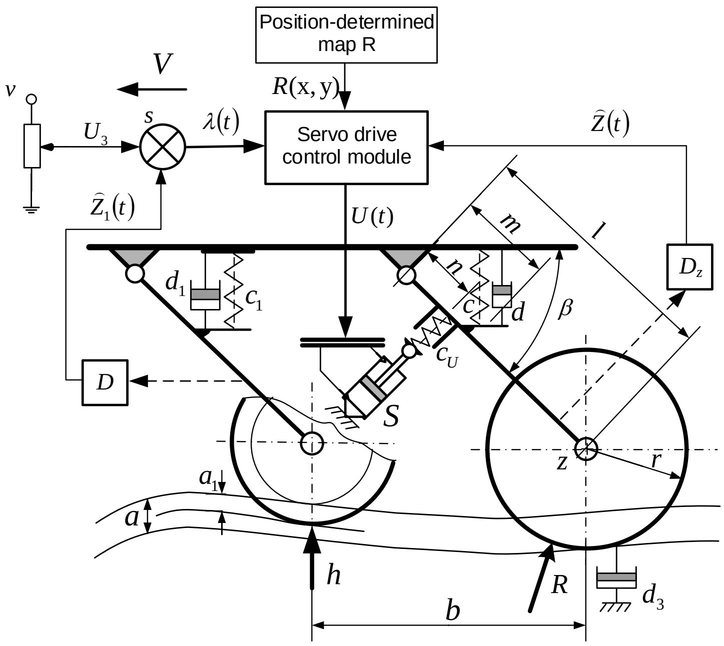

Fig. 3 - Scheme of a two-phase coulter system with an automated indenting disk correction system

Fig. 4 presents the scheme of an automated indenting disk correction system.

A signal *R(x,y)* is sent from the reading unit (PC card) of a soil map to the calculation unit of position-determined soil consistency. A signal *γ(x,y)* from a global positioning system sensor is applied to the same block. The output signal of this block is the signal *R(x,y,t)*, which is normalized relative to the amplitude and synchronized with the world coordinates. An output signal *λ(t)* serves as a tracking (purpose) signal. This signal is formed as a result of applying the signal $\check{Z}_1(t)$ from the sensor *D* of a slot cutter position and the signal $\check{Z}_1(t)$ from a feedback sensor D_Z that controls an indenting disk position to an adder unit. A setter *3* with an output signal $U_з$ is used for manual controlling of an indenting disk position relative to a slot cutter. On one hand, the purpose is achieved by means of managing slot cutter running at the depth α_1, on the other hand, it is reached by the influence of a pneumatic drive on the drawbar of the radial hanger of an indenting disk (controlled by a sensor D_Z with an output feedback signal $\check{Z}(t)$). As a result, the target seeding depth *Z(t)* is achieved at the output of the system.

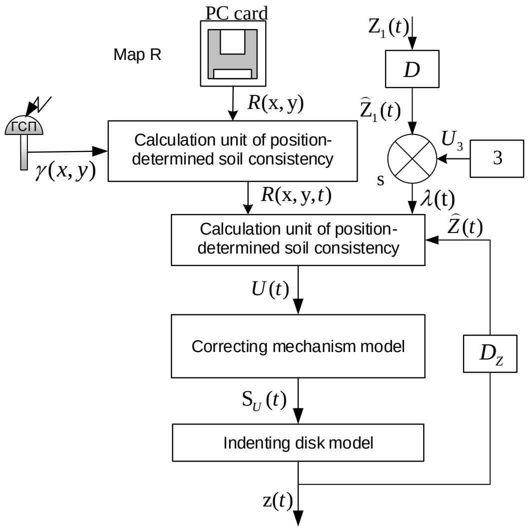

Fig. 4 - Scheme of an automated indenting disk correction system

The main task of the control system is the calculation of the optimum value of the control action *U(t)*, which is applied to the correction mechanism of an indenting disk position. The rod of a pneumatic drive *S* (see Fig. 3) adjusts the position of an indenting disk relative to a slot cutter depending on the set adjustments, the irregularities of the field surface and the value of soil resistance according to the coordinates of a seeding unit in the field and the value of an indenting disk running depth. As a result, at the output of the system a specific position of an indenting disk *Z(t)*, as a signal function of the regulating action *U(t)* that comes from a pneumatic drive control module, is achieved.

A transfer function of an indenting disk model can be found by means of deriving a differential equation of an indenting disk movement. In order to formulate a dynamic equation of a coulter system motion along the irregularities of a field surface, let us apply Lagrange's dynamic equations of the second kind:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{q}_i}-\frac{\partial T}{\partial q_i}+\frac{\partial \Pi}{\partial q_i}+\frac{\partial \Phi}{\partial \dot{q}_i}=Q_{q_i} \quad (1)$$

where *T* and *Π* – kinetic and potential energy, respectively; *Φ* – dissipative function;

q_i – generalized coordinates; Q_{q_i} – generalized force.

Having determined the necessary components with their substitution in the dynamic equation (1) and having performed the necessary transformations, a dynamic equation of a coulter system motion along the irregularities of a field surface is obtained:

$$\ddot{z}\left(\frac{I\tan\left(\beta^2\right)}{R^2}+M\left(1+\tan(\beta)^2\right)\right)+\dot{z}\frac{\left(dm+ld_{\text{з}}\right)}{l}+z\left(\frac{cm}{l}+\frac{n^2\sin(\beta)^2c_U}{l^2}\right)-Q_U=S_U\left(\frac{n\sin(\beta)c_U}{l}\right) \quad (2)$$

A transfer function of the model of an indenting disk of a coulter system is of the following form:

$$W_{vd}=\frac{A_4}{A_1\tau^2+A_2\tau+A_3} \quad (3)$$

where $A_1 = \frac{I\tan(\beta)^2}{R^2} + M\left(1+\tan(\beta)^2\right)$; $A_2 = \frac{(dm + ld_з)}{l}$; $A_3 = \frac{cm}{l} + \frac{n^2\sin(\beta)^2 c_U}{l^2}$; $A_4 = \frac{n\sin(\beta)c_U}{l}$ τ – symbol of time differentiation.

A transfer function of the model of a servo-mechanism of an indenting disk position correction is of the following form:

$$W_{np} = \frac{K_k}{T_k^2\tau^2 + 2T_k\xi_k\tau + 1} \tag{4}$$

where K_k, ξ_k, and T_k – coefficient of amplification, a damping coefficient and the time constant of a position correction mechanism, respectively.

A transfer function of the sensor model of an indenting disk position is of the following form:

$$W_d = \frac{A_d}{T_d\tau + 1} \tag{5}$$

where $A_d = 1 + \Delta_d(t) + \xi_d(t)$; $\Delta_d(t)$ and $\xi_d(t)$ – systematic and random components of the relative error of sensor performance; T_d – sensor time constant.

The equations (4), (5) make a functional model of a two-phase coulter system. The analysis of such a model makes it possible to choose the structure and the parameter values of the control action *U(t)* (law of control), which can provide process stability of the system as well as its operation at the permissible error values when keeping track of the goal achievement.

In order to determine the ability of a two-phase coulter system to operate a specified working mode, if such operating parameters as, for example, the amplitude and the frequency of irregularities entering a coulter system, the mass of a slot cutter and an indenting disk, a damping coefficient ξ, an amplification coefficient *K* etc. are changed, given that there are systematic and random errors of measuring and control elements, simulation modelling has been conducted.

At the first stage of the simulation modelling, the influence of systemic and random errors on the performance of the position sensors of a slot cutter and an indenting disk, without taking into account a soil reaction component, was analyzed. As a result, it has been determined that it is necessary to apply sensors with the minimum values of systematic and random performance errors for high quality covering of seeds at the set depth.

The next step of simulation modelling was the evaluation of soil consistency influence (the main component of soil reaction on a slot cutter) on the quality of an indenting disk performance. This influence is difficult to explain, since, as a result of the laboratory-field investigations on measuring soil consistency at the seeding depth under the field conditions, this value was determined to be within the range of 100…1300 kPa.

In order to conduct laboratory-scale and laboratory-field investigations, a laboratory-field plant has been designed and developed (Fig. 5).

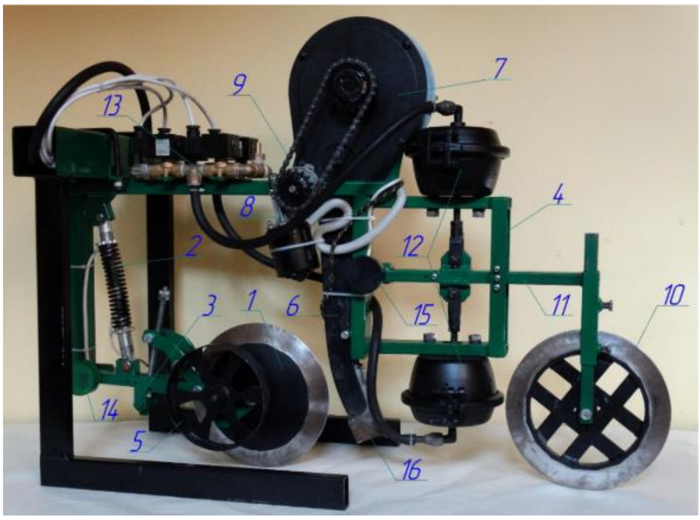

Fig. 5 - General view of a laboratory-field plant

1 – slot cutting disk; 2 – shock absorber; 3 – drawbar; 4 – frame; 5 – supporting-running wheels; 6 – seed line; 7 – seed-feeding unit; 8 – electric motor reductor; 9 – chain drive; 10 – indenting disk; 11 – hanger; 12 – pneumatic cylinders; 13 – valve actuating gear; 14, 15 – position sensors of hangers; 16 – inductive sensor

The laboratory-field plant is a two-phase coulter system consisting of a slot cutting disk *1*, which is hinged to a frame *4* via a drawbar *3*, which is spring-loaded by a shock absorber *2*. The running depth of a slot-cutting disk is regulated by means of supporting-running wheels *5*. There is a seed-feeding unit *7* with a seed line *6* arranged lengthways in series. An indenting disk *10* is arranged on a hanger *11*, which is hinged to frame. A seed-feeding unit is actuated by means of electric motor reductor *8* through an electric chain *9*.

The two-coulter system has an automated position regulation and control system of an indenting disk, which, in its turn, consists of two pneumatic cylinders *12*, a valve actuating gear *13*, position sensors *14* and *15* of hangers, an external compressed air supply (it is not presented in the Figure) and Mikrol MIK 121 controller that controls the operation of a seed-feeding unit as well. In order to record the moment when a seed enters the bottom part of a seed line, an inductive sensor *16* is installed.

In the course of conducting laboratory-field investigations, the suggested coulter system was mounted on a 16-row John Deere 7000 planter (Fig. 6), which was utilized with John Deere 8400 tractor, instead of its commercial thirteenth row unit. Seeding units were the same on all the planter units (pneumatic, vacuum-type, equipped with an individual electric drive) and set for the same seeding rate.

Fig. 6 - A two-phase coulter system on John Deere 7000 planter

All the investigations were conducted according to the standard complete factorial procedure. The defined optimization criteria included the following: the uniformity of seed dropping distance along a row, the uniformity of seeding depth, soil consistency in the area of seed location and seed germination capability. Experimental data processing was conducted with the use of Statistica application software package.

An investigation on the quality of seed covering by means of a two-phase method and on determining the nature of the soil area firmed by an indenting disk has been conducted in a tillage bin. Soil moisture content at the moment of conducting the research was brought to 20±2 % and controlled by means of FIELDSCOUT TDR 300 Soil moisture tester.

With the help of the developed laboratory-field plant, the difference in the running depth Δh of a slot cutter and an indenting disk, which was necessary to provide soil consistency Q in the area of seed depth within the limits of 1.1…1.3 g/cm^3, was determined in a tillage bin. Before the beginning of the experiment soil moisture was brought to 20±2 % and the soil was tilled to reach the average consistency of 1 g/cm^3. The consistency formed at the seed depth was determined according to Kachynskyi method, however, a specially designed sampler 8 cm^3 in size was applied.

Parameter Δh was changed at three levels: 1 cm, 2 cm and 3 cm.

RESULTS

On condition that all the above-mentioned values of the dynamic parameters of a two-phase coulter system are applied, the result of solving the process of its functioning according to the structural diagram of the automated correction system of an indenting disk position is presented in Fig. 7.

Fig. 5 shows that the functioning mechanism of an indenting disk (*Z(t)* coordinate) has the transient process of 0.35 s at the beginning of its operation. Besides, there is a phase displacement of 0.27 s in copying field surface irregularities that, for example, in case of the running speed of a planter being 2 m/s, corresponds to the copying with the displacement of approximately 0.54 m. In addition, the set amplitude of an indenting disk's oscillations is not maintained. For example, from the 3rd to the 9th second time period, the amplitude of irregularity oscillations is equal to 9.8 cm, while the amplitude of an indenting disk oscillations within the same time period is only 7.5 cm. However, the most significant moment is the negative influence of soil reaction *Rg* on the process of copying irregularities. As it can be seen in Fig. 7, the raising of an indenting disk takes place with the failure of the copying process up to 1.8 cm.

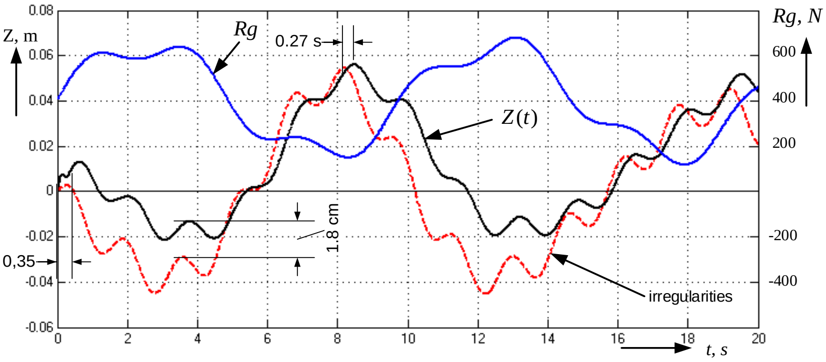

Fig. 7 - Representation of the operation process of the two-phase coulter system
Z(t) – coordinate of an indenting disk position; Rg – value of soil resistance force

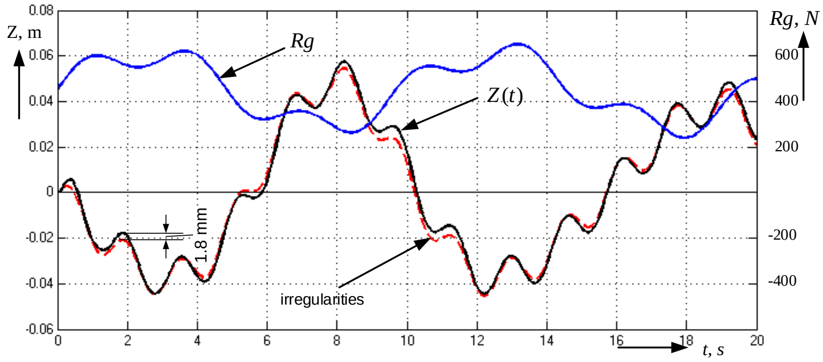

Fig. 8 - Representation of the operation process of the improved two-phase coulter system
Z(t) – coordinate of an indenting disk position; R_g – value of soil resistance force

It is to the point to have a system with steady and set modes of copying field surface irregularities, which is invariant with respect to the effect of soil reaction on an indenting disk. Computer simulating modelling made it possible to determine the influence factors for the achievement of the set goal. The main factors include spring stiffness c_U (see Fig. 3), the decrease of damping coefficient *d* as well as a time constant, the decay coefficient and the amplification coefficient of the control module of a pneumatic drive. Fig. 8 presents the operation process of the system at the values of c_U=360 kg/cm, d=120 N s/m, t=0.1 s, ξ=0.1, K=4.9.

The measure of inaccuracy *I* in evaluating the running depth of an indenting disk relative to the set one during the standard operation period *T* of a coulter system was equal to 1.5×10^{-4}.

In general, the achievement of the goal of maintaining the set running depth of an indenting disk of a two-phase coulter system is satisfactory. The dynamic parameters of the system are chosen in such a way that the changes in position determined soil consistency (by means of the parameter *Rg*) do not have a significant influence on the running stability of an indenting disk, its raising is reduced to a minimum and does not exceed 1.8 mm. In addition, there is no phase displacement in copying field surface irregularities.

The conducted research shows that soil consistency in the field area, which is cultivated for planting crops, varies widely (up to 1300 kPa) and does not have the dominant variation frequency along the run of cultivated land. These results were taken into account when determining the post-conditions of the simulation modelling of the operation process of a two-phase coulter system.

On the surface of the soil a slot was made by means of a slot cutting disk and a seed was fed to it. Afterwards, an indenting disk was pulled along the slot. It cut the soil from the furrow walls and covered the seed (Fig. 9 *a*). As it can be seen, after the pass of an indenting disk, there was an area of firmed soil formed (Fig. 9 *b*) – top view and cross-sectional view (Fig. 9 *c*).

Parameter ***v*** was changed at three levels: 1 m/s, 1.7 m/s and 2.4 m/s.

a) b) c)

Fig. 9 - Representation of the implementation of a two-phase method of seed covering
a – indenting disk operation; b – firmed soil area (top view); c – soil cross-sectional view

Simultaneously, the influence of the running speed ***v*** of a two-phase coulter system on the optimization parameter of ρ was evaluated.

The response surface of the change in soil consistency ρ depending on the parameter Δh and the running speed ***v*** of a two-phase coulter system has been built (Fig. 10).

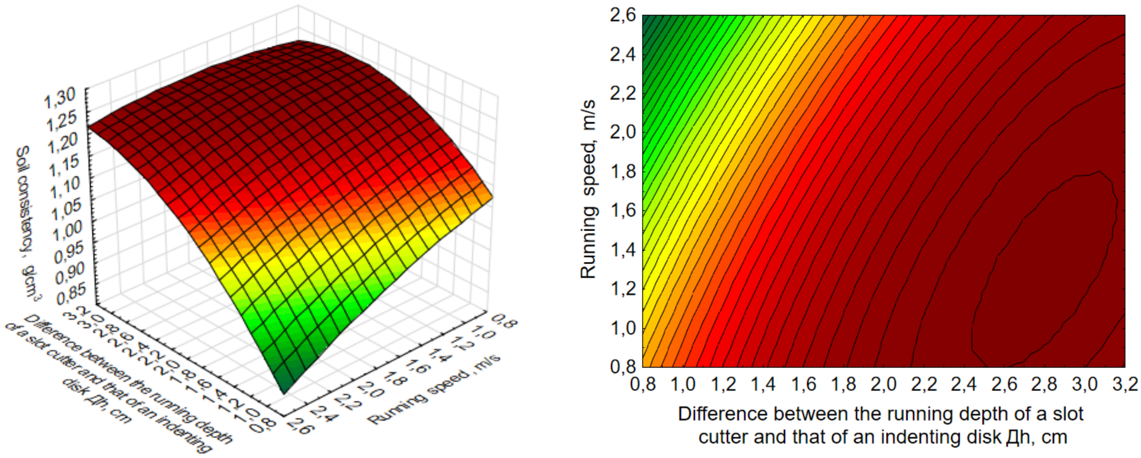

Fig. 10 - Response surface of the change in soil consistency *ρ* depending on the parameter *Δh* and the running speed *V*

As a result of the conducted complete factorial experiment 3^2, a regression equation in natural values has been obtained.

The obtained regression equation determined the dependence between the optimization parameter of ρ and the following parameters: running speed of a coulter system V and the difference in the running depth Δh of a slot cutter and that of an indenting disk, which is the most influential parameter. According to the defined conditions the optimal values are the following Δh_{opt}=2.802 cm, V_{opt}=1.29 m/s.

Laboratory-field investigations, aimed at determining the change in the variation coefficient of seed covering depending on the running speed of a planter and the running depth of a coulter, have been conducted. The investigations were conducted in field № 6 of Agronomic Research Station during corn planting. The soil was low-humic typical chernozem and its moisture content ranged within the limits of 18…22 %. The depth of seed covering was determined after the germination by means of measuring the ethylated part of a plant. The test was conducted with two factors at three levels. The running speed of a planter ***v*** was set at three levels: 1 m/s, 2 m/s and 3 m/s, coulter running depth h was set to be 3 cm, 5 cm and 7 cm. As a result of the obtained data processing, a response surface has been plotted (Fig. 11).

The regression equation that determines the dependence between the optimization parameter of W and the following parameters: the running velocity v of a coulter system and the depth h of seed covering. In this case, the speed h is the most influential factor.

In order to obtain comparative evaluation of a two-phase coulter system operation under the field conditions, variation coefficients of seed covering depth, the distance between the plants in a row, field germination capability of seeds and the average soil consistency in the area of seed location have been determined.

All the indices were determined after the germination by means of measuring thirty sequentially placed plants in five different areas. The thirteenth (a two-phase coulter system) and the fourteenth rows of a planter have been compared. Fig. 11 represents the processed data of the measurements.

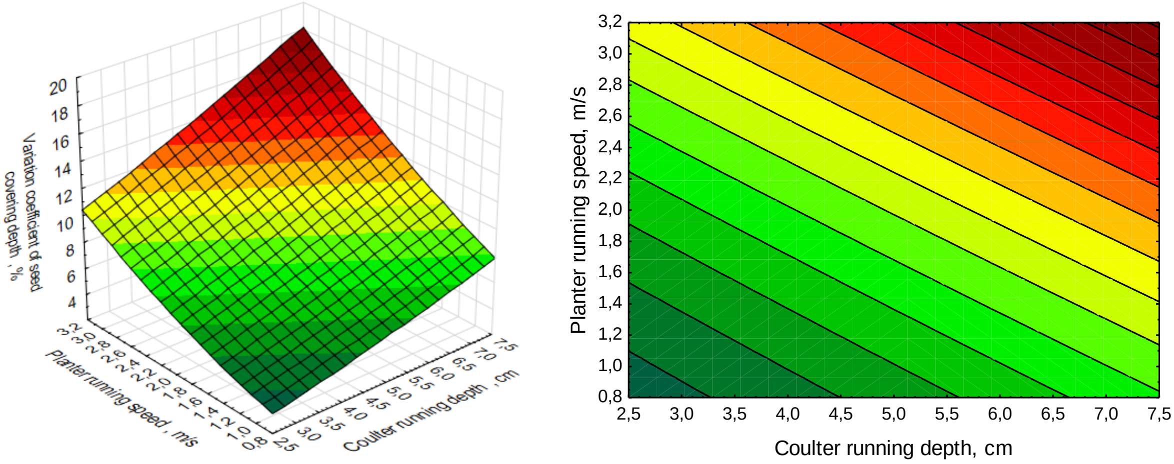

Fig. 11 - Response surface of the variation coefficient of seed covering depth *W* depending on the running speed of a planter *V* and the set running depth of a coulter *H*

Fig. 12 shows that the variation coefficient of seed covering depth decreases in 2.1 times, the variation coefficient of the distance between the plants decreases in 2.9 times and field germination capability increases in 8.8 %. Here, the value of the average soil consistency in the area of seed location increases from 1.02 g/cm^3, when planting is performed by means of a basic coulter system, to 1.18 g/cm^3, when sowing is realized by the suggested coulter system, which is within the range of optimal values 1.1…1.3 g/cm^3.

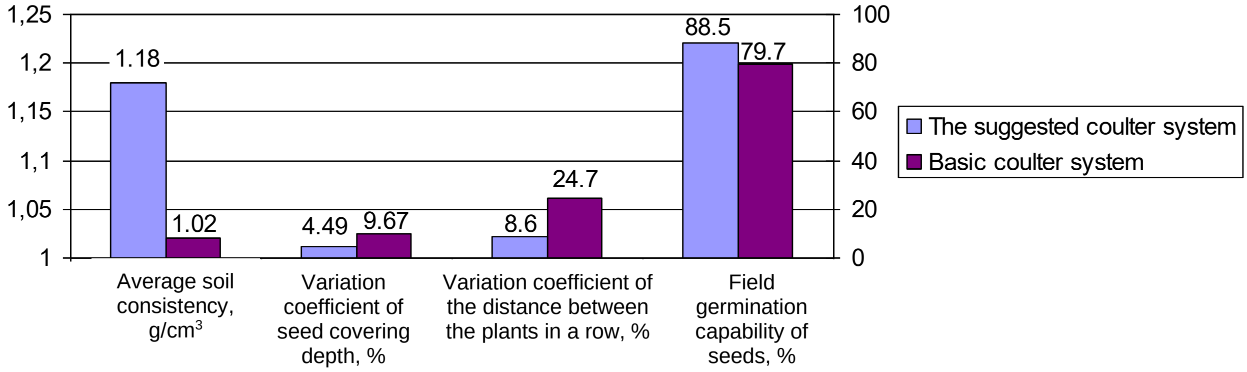

Fig. 12 - Value of the variation coefficient of seed covering depth, %; variation coefficient of the distance between the plants in a row, %; field germination capability of seeds, %; and the average soil consistency in the area of seed location, g/cm^3

CONCLUSIONS

- The advanced way of the improvement of the sowing process by means of applying a two-phase coulter system has been substantiated based on the conducted analysis of the existing ways and the facilities for sowing tilled crops.
- A mathematical functional model of a two-phase coulter system for row-crop planters has been developed and the simulation modelling of its operation has been conducted, which has made it possible to determine the influential factors for the set goal achievement. These main factors include the spring stiffness c_U=360 kg/cm, the damping coefficient d=120 N s/m, the time constant T=0.1 s, the decay coefficient ξ=0.1 and the amplification coefficient K=4.9 of a pneumatic drive control module.
- Theoretical and practical analysis of the interaction of the operating elements of a two-phase coulter system and the soil as an integral dynamic system has been conducted and the interrelation of a slot cutter and an indenting disk operation process has been substantiated. The optimal value Δh_{opt}=2.802 cm of the difference in the running depth of a slot cutter and that of an indenting disk, which is necessary for the formation of soil consistency within the limits of 1.1…1.3 g/cm^3 in the area of seed location, has been determined.

- Experimental investigations on the influence of the substantiated design parameters of a two-phase coulter system on seed distribution in the soil show that there is a decrease in the variation coefficient of seed covering depth in two times (from 9.67 % to 4.49 %), a decrease in the variation coefficient of the distance between the plants in almost three times (from 24.7 % to 8.6 %), an increase in seed germination capability for 8.8 % (from 79.7 % to 88.5 %), an increase in the average soil consistency in the area of seed location from 1.02 to 1.18 g/cm^3 compared to a basic coulter system.

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