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The Analysis of the Technological Process of Row Crop Cultivator using the Laws of Classical Mathematics.

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***Abstract:** The article presents a model for treatment information when performing a cultivator technological process, presents the results of the probabilistic characteristics of the processes in the functioning models of cultivating aggregates.*

A mathematical model of the system "tractor-cultivator with working bodies-soil" has been developed. The hypothesis that the error of the additional protective zone obeys the law of normal distribution has been chosen. An algorithm has been developed for calculating the statistical series of deviations from the protective zone. For acceptance or rejection of reliability, the initial hypothesis that the deviation of the additional protective zone obeys the law of normal distribution can be selected and verified by the Pearson criterion. Constructed graphs of normalized spectral densities of the width of the protective zone and analyzed the probability of damage to plants. A histogram of the distribution of deviations of the width of the protective zone and a graph of the theoretical distribution density are constructed. Based on the results obtained during experiments with a cultivator model, the hypothesis is confirmed or refuted. If this is confirmed, an acceptable value for the width of the protection zone is presented. Therefore, based on these studies, it is possible to determine the width of the protective zone by inter-tilling of row crops.

***Keywords:** cultivator aggregate model, protective zone, agrotechnical assessment, tests, plant lines.*

I. INTRODUCTION

Agricultural aggregates and their complexes are complicated dynamic systems which operate under the conditions of changing external influences due to numerous and diverse factors. In this regard, in the calculation and design, as well as in tests and studies, agricultural aggregates should be considered as controlled dynamic systems consisting of a number of interconnected subsystems (components of the aggregate, processed medium, control devices, etc.).In this case, there is a need to build a design scheme which would most fully reflect the real operating conditions of the aggregate. This scheme can be considered as a model of the aggregate, since it reflects the most significant aspects of the work process performed by the aggregate. Understanding the working principle of a machine theoretically, afford to re-design it without performing the recast process. [1,2,3]

In the theory of agricultural machines, deterministic models of processes in which each variable or parameter changes quite definitely and takes exactly fixed values in any given conditions are most used. To such models include any equations (algebraic, differential, etc.) that characterize strictly defined process changes. In the practice of statistical calculations of agricultural aggregates, various probabilistic models of processes are used. Most often, models of random variables and random functions are used for this purpose. [4]

When cultivating irrigated crops, row-spacing is carried out using a cultivator that scratches the soil, removes weeds and cuts irrigation furrows. The models of row cultivators functioning can be presented differently depending on the type of operations performed and the consideration of various factors. The most acceptable model can be considered three-dimensional with input variables of the profile of the field surface, soil resistance and configuration of a row of plants.

For example, when considering the dynamics of row cultivators, due to the oscillation of the aggregate in the longitudinal-vertical plane, oscillations of the working bodies also arise, which negatively affects the uniformity of the depth of hoeing (G. N. Sineokov, 1977). Reasoned and in detail expound the issues of influence the dynamic facts on traction resistance and related opportunities for improving the energy of tillage operations (A. S. Kushnarev, 1981).

It can be noted that the experimental research method in this area is unproductive, since it does not allow us to estimate the parameters of the vibration regimes. Of great interest are theoretical studies, which make it possible to evaluate the process of interaction of an oscillating working body with soil on generalized mathematical models. For example, on the study of the oscillations of the working bodies, the working body on the stilt, interacting with the soil environment may be considered as a system with distributed parameters, under the influence of distributed load, since the mass and load are distributed along the length of the stilt (Burchenko P. N.,1997, Vasilenko P. M., 1995, Lurie A.B., 1981). On the development and analyze a dynamic model of the loading of working bodies on elastic stilts, noticed that the study of the oscillations of the working body on an elastic stilt is possible by mathematical modeling of the load of elastic stilts, using the methodology of the classical theory of elasticity. When considering such a body, the theory of elasticity proposes to consider plane deformation or plane tension state (Kononenko E.V. 1969, Chatkin M.N., 2010). Solving the obtained models by analytical methods by substituting the elastic stilt parameters and taking into account the initial conditions is laborious.

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Is proposed to implement these models by the finite element method (FEM) using software systems. They, along with obtaining specific parameters of the elastic stilts, allow you to visualize the process of modeling and establishing optimal parameters of systems. These actions are comparable to conducting experimental studies at the design stage of an elastic stilt for certain operating conditions in the process of tillage (Dmitriev S.Yu., 2007).

A mathematical model which takes into account a number of dynamic effects of the process of soil destruction is presented, while in this model, mainly low-frequency vibrations of the working body are considered. The kinematic diagram of the working body is an elastic system with a concentrated mass under the action of a generalized force. The perturbing force is a random function of the state of the system in time, characterizing the geometry of cutting and the coordinates of the displacement of the working body. The energy effect of elastic fastening is represented by the displacement transformation operator, that is, it is associated with the average value of the elastic displacements and the standard deviation of the studied process. The first factor causes a distortion of the geometry and cutting conditions, and the second vibration acceleration of the working body (Ignatenko I.V., 2003).

A mathematical model of the system “tractor cultivator with elastic stilts - soil” was developed, and the resistance force is represented by a nonlinear dependence in the velocity function. It is shown that in the adopted mathematical model, the appearance of self-oscillations and relaxation vibrations is possible, a method for calculating their parameters by the harmonic balance method is proposed. Theoretical analysis of self-oscillating and relaxation regimes of operation showed the advantage of the latter. The design of the stilt is substantiated and proposed. An algorithm has been developed for calculating the main regimes of soil cultivation in order to achieve the maximum fuel economy effect. The input parameters of this algorithm are the tractor mass, the spring stiffness of stilt, the moment of inertia of stilt, the drag force, the stilt weight and their number. The assumption is justified that in the case of a change of the translational speed of tractor from a change in soil characteristics, some vibrations transfer to others while maintaining the vibration effect of the working body (Donchenko M. A., 2004).

For development of a theoretical calculator concerning the torque and power requirement of active tillage machine a thorough mechanical model for a rotary tiller is developed which contains both kinematics and kinetics viewpoints of its operation. This model relates the output parameters (the required torque, specific work and power of a rotary tiller) to some input parameters (the soil, the machine and the working state parameters). To perform the required calculations simply, and automatically, the derived equations were entered into an Excel spreadsheet, and the results was presented as the torque and power of a rotary tiller. The developed formulas were verified by comparing the results of the model with the acquired results of other studies (Iman Ahmadi, 2016). The comparisons had closely aligned results for all cases; therefore, this model can be used in studies that are about the torque and power requirementsof a rotary tiller.

A dynamic model of an elastically fixed working body with soil was developed, which is a matrix-vector equation in canonical form in the state space. Informativeness and generality allows us to use it to solve the problems of dynamics and optimize the design parameters of the working body and elastic fastening. The phase coordinates of the matrix-vector equations are the elastic displacements of the working body and their speed, which allows you to fully take into account all the features of the problem (three-dimensionality and spatiality, nonlinearity and self-oscillation, inertia and stochasticity) and to give the form of fundamental relations. A feature of the proposed mathematical model is the presence of feedback, which leads to the emergence of some dynamic effects, inexplicable without taking into account the feedback. Feedback means the change in the resistance force of the working body under the action of its elastic displacements (Denisova O. A., 2017).

A dynamic model of the movement of cultivator working body with elastic attachment to the frame of the tillage implement was developed, which allows one to obtain calculated oscillograms of the angle of twist of the cultivator stilt relative to the hinge. Subsequent mathematical processing, which allows you to determine the values of the standard deviations of the angle of twist and the mean square values of the depth of tillage as a function of the design parameters of the cultivator stilt and dissipative soil properties, as well as determine the technological tolerances for changing the stiffness of the elastic element in the fastening of the working body (Ignatenko I.V., 2003).

Statement of the problem

The quality of the cultivator's work when cultivating the soil in row-spacings is the uniformity of the depth of cultivation $a(t)$ and the consistency of the width of the protective zone $l(t)$. The highest quality of work will be in the event that the trace $y_{kl}(t)$ of the utmost to row working body (chisel) copies the row line $y_p(t)$. The error $\varepsilon(t)$ between the established (adjusted) boundary of the protective zone $y_o(t)$ and the path $y_{kl}(t)$ of the utmost working body (chisel) determines the deviation of the actual width of the protective zone $l(t)$ from the given value l_o, and $l(t) = y_{kl}(t) - y_p(t)$.

If we take as a first approximation that the process $l(t)$ is caused only by the lateral movement of the aggregate in the horizontal plane and its passing is not affected by the oscillations of the aggregate in the longitudinal-vertical plane, then the process of treatment the information $y_p(t)$ is carried out by the aggregate through the driver *1*, steering gear *2*, tractor *3* and cultivator *4* (Fig. 1). In the calculated scheme for analyzing the output process $l(t)$, the aggregate can be represented as a series connection of four links. In this case, the output signal for the first link (driver) will be the turn of the steering wheel $\varphi_P(t)$, for the second link (steering mechanism) - the turn of the steering wheels $\varphi_k(t)$, for the third link (tractor) - the turn of the longitudinal axis of the tractor $\varphi_t(t)$. As a result of this turn, the longitudinal axis of the cultivator (fourth link) will also be turned by a certain angle, which determines the corresponding width $l(t)$ of the protective zone.

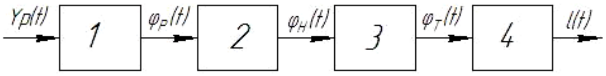

Fig.1. The model of treatment information Yp (t)

In order to avoid damage to the plants in rows, the edges of the cultivator's working bodies are placed at the width of the protective zone *L*, on the first cultivation, at *L = 8 ... 12 cm*, on subsequent *L=14 ... 15 cm* [19].

The protection zone consists of two parts (Fig. 2):

$$L = l_0 + l \qquad (1)$$

where l0 is the value of the root part, mm, *l* is the value of the additional protective zone, mm

The root zone l0 is a quantity that depends on the structure and size of the crop root and soil properties.

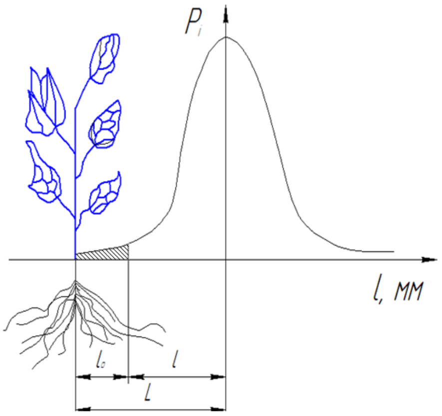

Fig.2. Scheme for calculation the width of the protective zone

The value of the additional protective zone *(l)* depends of the size of the inevitable deviation from the equidistant movement of the working body in the row-spacings during cultivation. The error (ΔL_i) of the value of the protective zone *(L)* is equal to the error caused by the inevitable deviation of the working body of the cultivator (ΔL_i) during movement, $\Delta l_i = \Delta L_i$. Because at a certain period in the development of culture l_0 = const. This indicates that the error of the additional protection zone *(l)* can be determined by the error of the protective zone (*L*) (l).

There are various reasons why the additional protection zone *(l)* changes. For example, the correctness of the rows of plants, the kinematic parameters of the cultivating aggregate, the properties of the soil, the profile of the furrow, the skills of a tractor driver and much more.

From probability theory, we know that a sufficiently large set of random values obeys the law of normal distribution, even if these values are not interrelated, [20-21]. From the above, one can choose the initial hypothesis that the error of the additional protective zone (Δl_i) obeys the law of normal distribution.

II. SOLUTION METHOD

We chose the hypothesis that the error of the additional protective zone (Δl_i) obeys the law of normal distribution.

The law of normal distribution has the following probability densities:

$$P_i = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{l_i - \bar{l}_i}{\sigma}\right)^2} \qquad (2)$$

where *σ* is the root-mean-square deviation;

$\bar{l}_i$ is the arithmetic mean deviation;

l_i is the corresponding size of the protective zone.

The arithmetic mean deviation from the values of the protective zone is determined as follows:

$$\bar{l}_i = \frac{\sum_i^n l_i}{n} \qquad (3)$$

where *n* is the number of measurements.

The root-mean-square deviation is calculated by the following formula:

$$\sigma = \sqrt{\frac{(\Delta l_1)^2 m_1 + (\Delta l_2)^2 m_2 + \ldots + (\Delta l_i)^2 m_i}{n}} \qquad (4)$$

where $\Delta l_i = l_i - \bar{l}_i$ is the number of measurements in intervals.

With multiple measurements (100 or more), a statistical line is compiled. To do this, the entire error range (Δl_i) is divided into intervals and the number of measured values (m_i) for each *i*-interval is calculated. The frequency for each interval is determined from the expression.

$$P* = \frac{m_i}{n} \qquad (5)$$

For a graphical representation of the statistical line, a histogram is compiled. To construct a histogram on the abscissa axis, the width of the interval is laid aside and regular rectangles are plot. In order to find the correct rectangle height, it is necessary to divide the frequency (P_i) for each interval by its width (group size). As a result, the surface area of the rectangle of each group is equal to the frequency of this group, and the sum of the surface areas of all the rectangles is unity.

To accept or reject the selected hypothesis that the error of the protective zone obeys the law of normal distribution, the correspondence of the theoretical and statistical distributions is checked using χ^2 (Pearson criterion).

Correspondence is calculated using the following formula:

$$\chi^2 = \sum_{i=1}^{k} \frac{\left(m_i - nP_i^*\right)}{nP_i} \qquad (6)$$

where *k* is the number of groups;

P_i - is determined from formula (2)

The correspondence of the values (χ^2) is also a random variable, its distribution is related to the quantity *(r)*, which is called the “degree of freedom” of the distribution

$$r = R - S \qquad (7)$$

where *S* is the number of freedom conditions specified for the frequency *P**.

In this case, the following three conditions are required, (*S* = 3):

a) $\sum_{i=1}^{k} P_i^* = 1$; the sum of the frequencies is equal to one. This condition is always established.

b) $\sum_{i=1}^{k} P_i^* = \bar{l}$ the theoretical distribution should be chosen so that the arithmetic mean of the statistical expectation and statistical deviation is equal.

c) $\sum_{i=1}^{k} (l_i - \bar{l}_i) P_i^* = D$ condition for the correspondence of theoretical and statistical variances;

R is the probability that the value of the compliance indicator for random reasons is not less than the value calculated by the experiment (6).

III.RESULTS

The experiments were carried out using a model of a cultivator aggregate. To do this, lines of rows of plants are randomly applied on graph paper. Plant row lines may consist of periodic curves. The cultivator model is equipped with writing devices installed in the places of attachment of the working bodies. Thus, the process of row-spacing tilling by the cultivator aggregate is simulated. The model is manually guided between the rows. And the lines that are drawn by the working bodies (trajectories of movement) make equidistant movements along the row-spacings. The protection zone is measured after 10 mm.

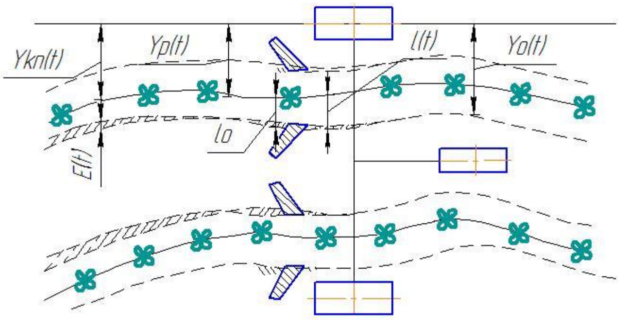

Fig.3. The trajectory of the points of the cultivator working bodies

Measurements are taken to the right or left of the row (Fig. 3). The measurement results are recorded in Table 1.

Table 1.

Deviation of the working bodies of cultivator aggregate model from the protective zone during row spacing

№	Results of experiment, mm	№	Results of experiment, mm	№	Results of experiment, mm
1	11	11	7	21	10
2	10	12	7	22	12
3	9	13	9	23	11
4	8	14	10	24	12
5	9	15	11	25	11
6	10	16	9	26	10
7	11	17	8	27	10
8	12	18	8	28	12
9	11	19	9	29	10
10	8	20	8	30	9

Using the above results, as well as formulas (2), (3), (4), (5) and (6), we find the statistical series of deviations from the protective zone. In the calculations, the Excel program was used, the obtained data are presented in Table 2

Table 2

The statistical series of deviations from the protective zone

№	Interval, mm	Group error mm	Setting measurement results by groups	Number of measurements in groups m_i	Theoretical density *P(Δl)*	Frequency $P^*(\Delta l)$
1	7-8	7	*II*	2	0.02794	0.07
2	8-9	8	*IIIII*	5	0.12069	0.17
3	9-10	9	*IIIIII*	6	0.27074	0.20
4	10-11	10	*IIIIIII*	7	0.31545	0.23
5	11-12	11	*IIIIII*	6	0.19090	0.20
6	12-13	12	*IIII*	4	0.06001	0.13

If the probability *P* is very small, that is, the value of the degree of compliance is actually less than the experimental result for random reasons, the experimental results contradict our hypothesis. In this case, the selected normal distribution is rejected, and based on the results of the experiment, the new distribution law (new hypothesis) is again checked by the criterion χ^2 [22-25].

If the error of the working body of the cultivator (Δl_i) is really true to the distribution law, the probability *P* is relatively high (usually *P*>0.1). In this case, the difference between the theoretical and statistical distribution is considered partial and due to random reasons. In this case, the value of the protective zone will be determined so that the probability of damage to the plant does not exceed the permissible limits.

Based on the statistical series of deviations from the protective zone, we construct a histogram of the distribution of the protective zone (Fig. 4) .

The permissible amount of plants damage is a prerequisite for the creation of additional protective zones. In order for the condition to be fulfilled, the probability of plant damage should not exceed δ. The working body of the cultivator should be located at a distance *(L)* from the plant, so that its probability of approaching to plant at a distance greater than l_0 does not exceed δ.

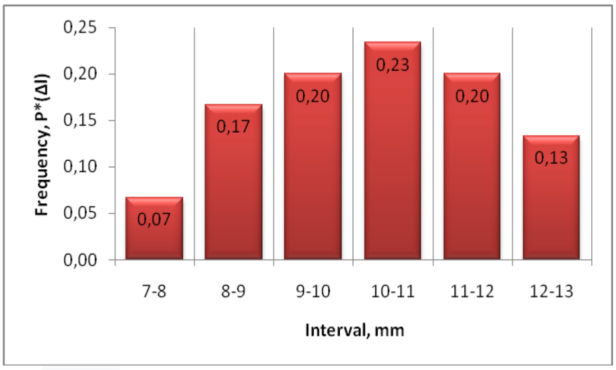

Fig.4. The histogram of the distribution of deviation of the protective zone's width

For this, it is necessary to ensure that the value of the normal distribution function *F* (l_i) is equal to δ:

$$\delta = F(l_i)\frac{1}{\sigma\sqrt{2\pi}}\int_{\infty}^{l} e^{-\frac{1}{2}\left(\frac{l_i-\bar{l}_i}{\sigma}\right)^2} dl_i$$

This integral is not represented by an elementary function; therefore, it is calculated by converting into a function the probability integral.

Probability integral

$$\delta = F^*(l_i)\frac{1}{\sqrt{2\pi}}\int_{\infty}^{l} e^{-\frac{t^2}{2}} dt$$

When changing a variable

$$t = \frac{l_i - \bar{l}_i}{\sigma} \text{ and } \bar{l}_i = 0, \ \sigma = 1$$

the function is represented as a probability function according to the law of normal distribution. This function is called the standard normal distribution function, and its values are given in tabular form [7]. When expressing the normal distribution function $F(l_i)$ with parameters σ and l by the standard function with normal distribution $F^*(l_i)$, we obtain

$$F(l_i) = F^*(\frac{l_i - \bar{l}_i}{\sigma}).$$

Now we can determine the probability that the random value l_i is in the range from $-\infty$ to l_0:

$$P(-\infty < l_i < l) = F^*(\frac{l_i - \bar{l}_i}{\sigma}) - F^*(\frac{-\infty - \bar{l}}{\sigma}) = F^*(\frac{l_i - \bar{l}_i}{\sigma})$$

where $F^*(\frac{-\infty - \bar{l}}{\sigma}) = 0$

default

$$\delta = P(-\infty < l_i < l) = F^*(\frac{l_i - \bar{l}_i}{\sigma}) \qquad (8)$$

If the standard normal distribution function is equal to δ, the l_i value corresponding to the argument $(\frac{l - \bar{l}_i}{\sigma})$ is determined, then the value of the additional protective zone is determined from the expression $l_i = (\frac{l - \bar{l}_i}{\sigma})$.

$$l = l_i \sigma + \bar{l}_i \qquad (9)$$

The size of the protective zone is determined by the formula (1) (usually in laboratory conditions $l_0 = 0$.)

IV.FINDINGS

The information obtained during tests and studies of agricultural aggregates indicates that the processes during their operation (input and output) are random in a probabilistic-statistical sense. Therefore, there is a need for quantitative and qualitative assessments of processes and, first of all, in the selection of their corresponding probabilistic models, since in practice one has to deal with limited information about these processes. The considered models of processes observed during the operation of cultivator aggregates allow us to note that the vast majority of input and output processes that determine the functioning models of cultivator aggregates are essentially random in nature and their degree of determination is very weakly expressed. Therefore to describe random processes we introduce probabilistic characteristics, that allow to describe the properties of processes with one or another completeness. The initial data for establishing such characteristics are the realization of random processes obtained as a result of experiments. Using such characteristics, it is possible with a certain probability to predict the processes observed during the operation of cultivating aggregates. The same characteristics can serve as the basis for a reasonable choice of the parameters of the cultivating aggregate and for other technical and exploitative calculations.

A mathematical model of the system “tractor-cultivator with working bodies-soil (row line of plants)” has been developed. We have chosen the hypothesis that the error of the additional protective zone (*Δli*) obeys the law of normal distribution. An algorithm has been developed for calculating the statistical series of deviations from the protective zone. Our hypothesis determines whether or not the experimental results obtained using the cultivator aggregate model are consistent or inconsistent. If it matches, the size of the protective zone lying within the limits of the permissible damage to plants is indicated. Therefore, the size of the protective zone for cultivators during cultivation of crops can be indicated.

To accept or reject the selected hypothesis that the error of the protective zone obeys the law of normal distribution, we checked the correspondence of the theoretical and statistical distributions using χ^2 (Pearson criterion).

V. CONCLUSION

In our example, when the working body of the cultivator is located at a distance of *L= 10 cm* from the plant (width of the protective zone), the closest approach to the plant is determined, which is *l=7 cm*. Under these conditions, the probability of damage to the plants is *δ = 7%*. It can be noted that the value of the protective zone does not exceed its permissible value. The results of a simulated row-spacing processing by a model of a cultivator are consistent with experimental results.

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