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OPTIMIZATION OF THE TECHNOLOGICAL PROCESS OF THRESHING COMBINE HARVESTER

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To improve the operational quality of paddy combine it was proposed to include additional innovative operations in plant process of pre-threshing preparation of rice biomass with anticipating seeds selection which increases seeds separation, reduces injuries, forms stable operation of threshing-separating device of combine harvester.

Retrofit feeder house is a solution to ensure the stable uniform feed of assorted biomass into the threshing separation device. Equipped with tool package – harvester feeder house turned to the running control equipment for incoming flow of biomass.

The movement of threshed heap inside the modified geometry of feeder house with tools effectively affect on caulis, panicle of rice – screed, and brings the biomass vibration mode i. e., lead to the dynamic separation of rice headed seeds to threshing rotor. Vibration (tossing) of biomass make it possible for free rice seeds pass through caulis to the bottom of feeder house.

Development program of innovative driving devices of multifunctional rice seed harvester combine considered the development of preproduction explorational program ensuring the information on harvest loss during various rice harvesting, their separation between main harvester aggregates – collector, auger, elevator, threshing mill. It is proposed to combine, in a single complex, all the control parameters, subordinating their actions, into an active control device of the technological process, affecting the shapes of rolls formed from various varieties and yields of rice

Keywords: combine harvester, feeder house, technological process, optimization, working body, biomass

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1. Introduction

In the technological process of the harvester, a production line for threshing a heap of rice is laid, in which all mechanisms and devices must ensure the fulfillment of the main task – to evenly distribute biomass, produce high-quality threshing and obtain marketable grain as much as possible with a minimum of losses in the grown crop and energy costs [1].

The solution to the problem is the active management of rice biomass during the harvesting process, which raises a number of complex issues, including the algorithmizing of various complex technological processes (recognition of the harvest ripeness of rice grains, mowing, and selection, threshing of biomass and cleaning). And through mathematical (functional) modeling, which involves the study of structural diagrams of harvesting processes, the functions of the object, their numerical characteristics, changes in the object over time under various environmental conditions [2].

Rice growing farms are faced with the task of providing the population with environmentally friendly, high-calorie and high-quality rice, through the introduction of new technologies in the cultivation and harvesting of rice, which increase yields and improve product quality. The problems of mechanization of rice harvesting production processes are still relevant and require comprehensive solutions that combine the improvement of existing technologies with new progressive, less energy-intensive ones.

2. Literature review and problem statement

In papers [3, 4] noted that when studying the processes of operation of agricultural machines, three elements must be taken into account: the material being processed, the working body and the required energy. Therefore, an important problem of agricultural mechanics is still the development of energy-saving technologies in agricultural production. Considering that the growth of gross output is proportional to energy consumption, it is difficult to overestimate the importance of developing less energy-intensive processes and technologies for rice harvesting [5, 6]. The relevance of research on this issue lies in the fact that until now there has been no comprehensive approach to rice biomass, its state in relation to the formation process, the degree of impact of the mechanisms and devices of the rice harvester when leveling in the pre-threshing period, feed stability and other factors that have a decisive influence on the quality of rice grains.

An improved design of the feeder house is proposed, adapted to modern modifications of combine harvesters, equipped with a changing set (collection) of working bodies that create the surface geometry for control devices. Along which the moving heap of biomass is evenly distributed over the entire width of the threshing drum, the feed is stabilized, the load on the drum is reduced, the «microspring effect» creates conditions for the passage of the separated free grains to the bottom of the feeder chamber and allows early picking of grains from the heap in the zone with insignificant drum impact. Failure to comply with these factors leads to overloads and excessive losses of rice grain during selection and subsequent transportation along the production line to the threshing and separating device. Practice has shown the main reason – the unevenness of the roll in cross-section, the confusion of the stem, the caked roll, the difficulties of selection and transportation [6, 7].

In a number of studies [8, 9], certain recommendations are given on the adjustments of the threshing machine, at different humidity of biomass. However, the researchers came to the conclusion that combinations of grain moisture and straw are possible when it is impossible to meet the requirements for under-threshing and grain damage, at the same time by selecting the adjustments of the threshing machine.

When the moisture content of the non-grain part of the crop is over 20 %, which is always typical for rice, it is difficult to achieve the required quality of the hammer by adjusting the gaps, it is necessary to increase the number of revolutions of the drum. These circumstances suggest that there is a certain optimal combination of moisture ranges of the straw and grain parts of the threshing crop for the threshing device.

The basis of the modern theory of the technological process of threshing is the experimentally verified statement that the destruction of grain bonds with the panicle occurs under the action of elastic resonant vibrations arising in the zone of the whip strike on the stem and propagating along it to the panicle. Along with the main oscillatory system, there is also a feedback system due to friction in the fibrous flow of stems.

The theoretical foundations that determine the operation of threshing devices are based on energy indicators and design parameters and volumetric properties of the product without taking into account the qualitative indicators of the result of threshing.

An objective criterion for evaluating the threshing process, taking into account the qualitative indicators of threshing, was proposed [10, 11], which improved the homogeneous coordinate system.

Rational proposals that contribute to solving the problem, improving the quality of marketable grain, are embedded in the proposed rice harvesting technology. Considering in general, the impact of technological factors on reducing losses, it should be noted that there are controversial decisions on certain issues and they require further research.

The solution to the problems of reducing the injury of rice grains in the threshing device during the harvesting process must be considered from the point of view of finding and creating optimal conditions for their flow.

The basis of the modern theory of the technological process of threshing is the experimentally verified statement that the destruction of the bonds between the grain and the panicle occurs under the action of elastic resonant vibrations that occur in the zone of impact of the whip of the threshing drum on the stem and propagate along it to the panicle. Along with the main oscillatory system, there is also a feedback system due to friction in the fibrous flow of the stems.

In a number of studies [11–13], certain recommendations are given for adjusting the threshing apparatus, at different moisture content of the biomass. However, the researchers came to the conclusion that combinations of grain and straw moisture are possible, when it is impossible to meet the requirements for under-threshing and grain damage, at the same time by selecting adjustments to the threshing apparatus. And they note that modern rice grain harvesters have serious drawbacks:

– passive controllability of the heap in the threshing area (5–10 %);

– high sensitivity to feed unevenness up to 3 8.6 %;

– high humidity and strawiness of the crop mass (coefficient of variation 41.2 %);

– significant damage and injury to grain up to 24.8 %;

– losses of unthreshed and free grain, in chaff and straw descending from the straw walker up to 13 %.

Sources of crop losses have been identified:

– loose grains that did not fall into the bunker;

– cut and not cut, non-threshed and not caught in the threshing drum panicles.

– incomplete threshing and separation in the TSD, due to design flaws.

The analysis of the results of studies of the processes of rice biomass entry into threshing is allowed to conclude that studies of the process of pre-threshing activation and biomass management are not given deserved attention. As for the problems, in assessing the quality of the harvester, depending on the combination of layer thickness and the degree of pulling ability of the rice biomass, by the mechanisms designed for this, it should be noted that in such a formulation of the problem were not set and were not considered.

3. The aim and objectives of the study

The aim of the study is to finding optimal solutions of the technological process of threshing combine harvester. This will make it possible to improve the quality indicators of threshing rice biomass and increase the collection of non-traumatized rice grains with combine harvesting technology.

To achieve this aim, it is necessary to solve the following objectives:

– to construct regression equations for the technological process of threshing a rice harvester;

– to determine the ranges of rational values of the design and technological parameters of the control device for distributing the flow of a heap of rice biomass in an inclined chamber by the method of multifactorial and multilevel experiment;

– substantiate the control device by the biomass flow of the rice harvester.

4. Materials and methods

The main feature of the devices that control the flow of rice biomass in a rice grain combine is the improvement of the threshing process with the organization of collecting free grain that has separated from the panicles and is sandwiched between the stems inside the biomass moving to the threshing and separating device (TSD).

According to the new technology, it was proposed to separate free grain from biomass due to the advance in time, to reduce its passage into the zone of the strict threshing regime of the TSD, preventing excessive crushing of up to 15 % of the rice crop.

According to the new technology, it is proposed to reduce the passage of free grain from biomass into the zone of the hard threshing regime by a threshing-separating device (TSD) by advancing the separation of free grain from biomass, preventing excessive crushing of up to 15 % of the rice harvest.

In our research, additional innovative operations in the technology of harvesting rice with combines are proposed, which are innovations in the organization of work acting on heap biomass ahead of time, in the following systems:

– picking;
– servers;
– transporting;
– leveling;
– threshing-separating.

According to the method of active control of rice biomass, two control devices are proposed in the rice grain harvester described in the pre-patent [11] and the collection of working surfaces of devices for active control of the technological process. When harvesting high-yielding rice varieties, to ensure the supply of biomass in a thin evenly distributed layer, a control device is used in the form of an activator 6, Fig. 1. Installed between the header and the feeder house, the activator consists of a body and a special beater with a comb that transports the biomass to the feeder house. The beater, equipped with an eccentric finger mechanism, combs the biomass and directs it to the feeder chamber [12, 13].

The second control device, located in the inclined chamber, in addition to the slatted conveyor and, adjustable at the entrance and exit from the chamber by spring-loaded devices, on the bottom of the inclined conveyor, working bodies 5 controlling the flow of biomass are installed.

The collection of working surfaces of the biomass control device 5 in accordance with Fig. 2 is placed in the body 3 of the inclined conveyor, on the bottom there are corrugated profiles (Fig. 1). Slatted conveyor 4 with spreading bars.

The pulling ability of driving devices is understood as the time during which a unit area of the working surface interacts with rice biomass. The pulling apart of the biomass stalks depends on the constant and adjustable parameters of the control device, as well as on the operating modes.

When harvesting rice separately, the reel is removed from the combine, and a pick-up is installed instead of the cutting unit. When selecting a swath, the pick-up, capturing the biomass of rice, delivers it to the feeder house of the combine.

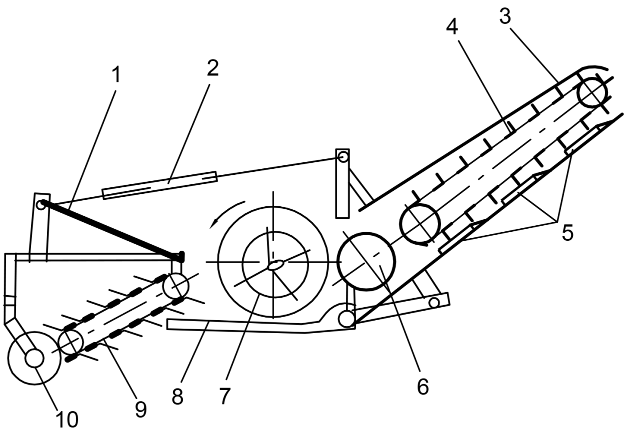


Fig. 1. A complex of mechanisms with control devices: 1 — tine; 2 — balancing device; 3 — feeder house; 4 — conveyor; 5 — driving tool; 6 — activator; 7 — auger; 8 — reaper; 9 — pick-up; 10 — support wheel

In the feeder house, the lower (driven) shaft of the conveyor drive is installed with bearing supports in vertical grooves, which provides a technological gap between the conveyor 4 and the bottom at the inlet.

When the conveyor moves, the biomass flow passes between the conveyor slats 4 and the bottom. On the bottom of the feeder chamber, the working body of the control device 1 (Fig. 2) is installed, made in the form of corrugated surfaces 2, where they, on the bottom of the feeder chamber, are located at different distances along the length of the feeder chamber. At the entrance to the feeder house, the distances between the corrugations 2 are larger and are directed away from the thresher. With such an arrangement of working bodies, the rice biomass tends to occupy free space and moves from the middle of the bottom of the inclined chamber to its edges. At the same time, in the inclined chamber, a smoother, smoother state of the flow of rice biomass along the depressions of the *V* – shaped profiles of the corrugations 2 is achieved. Their location among themselves contributes to this.

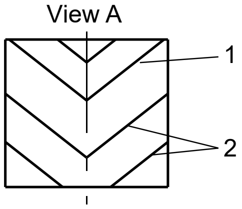


Fig. 2. Scheme of the working body of the rice biomass control device

Threshing of rice biomass flows, in the absence of a working body of the control device, leads to an increase in uneven loading of threshing and separating devices, adversely affects the productivity, quality, and energy of the rice grain harvester. The use of the driving tool of the leveling flow of biomass, when harvesting high-yielding and mixed mass of rice, leads to the alignment of the flow of biomass entering the threshing and separating device of the combine. The process of smooth and smooth leveling of the flow of rice biomass along the depressions of the *V* – shaped profiles of the working body of the control device along the width of the thresher. In turn, incomplete alignment of the flow of rice biomass along the width of the threshing machine does not ensure complete threshing of the grain, and mechanical damage to the grain increases.

The analysis of constructive and technological schemes of harvesters showed that the technological chain of mechanisms and devices, i. e. The production line for threshing rice, including working bodies, must be considered as a complex, combining them for the qualitative fulfillment of the main task – the active management of the heap of biomass entering the combine.

With separate rice harvesting technology, the combine is equipped with additional mechanisms and working bodies that ensure the selection of rolls lying on the stubble, transportation of packed biomass to the threshing and separating device.

One of the main biological features of rice culture is the non-simultaneity of grain ripening in the panicle, in connection with which, when picking up rolls and moving them inside the combine, the contact surfaces of the pick-up, auger, spacer with a beater, chain-slat conveyor of the feeder house affect them in addition to leveling and contribute to the separation of grain from the panicles to the threshing drum.

Rice grains separated from the panicles have the most valuable biological properties (large, not injured, full weight), it, together with the biomass (in the flow), moves to the TSD. The process of separating the grain from the panicles and transporting it along with the biomass flow needs active management and assistance, redistributing the biomass in thickness and width. In modern combines, the role of the distributor is assigned to the inclined chamber, practice has shown that the quality of distribution, i. e., flow control, is passive, as evidenced by the frequent overloads of the Mechanical Control System.

Considering the kinematics of moving a rice roll along an inclined chamber compressed by a slatted conveyor on the one hand, it should be noted that upon contact with the edges of the working bodies, the biomass experiences vertical shocks. The oscillatory nature of the impact on the biomass layer increases in amplitude as you move towards the TSD due to the height-changing parameters of the working bodies.

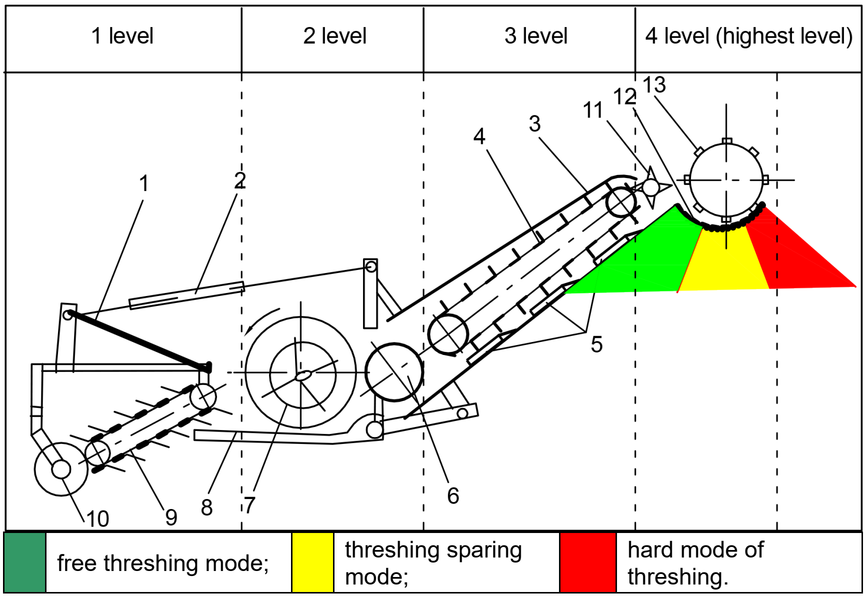


Fig. 3. Placement of control devices and their distribution according to the levels of impact on the technological process of rice threshing: 1 — tine; 2 — balancing device; 3 — feeder house; 4 — conveyor; 5 — driving tool; 6 — activator; 7 — auger; 8 — harvester; 9 — pick-up; 10 — support wheel; 11 — receiving beater; 12 — concave; 13 — drum

In accordance with Fig. 3, the layout of the control devices of a modern rice harvester is presented, conditionally divided into levels-the impact of the working bodies of the devices on the technological process of transporting biomass to threshing.

Instead of a reel, a pick-up 9 with stripping fingers is fixed to the header of the combine 8; for uniform travel of the pick-up 9 along the height of the mowed stubble, there is a supporting wheel 10, and a balancing device 2 with a pin 1.

The threshing process begins with combing, lying on the stubble-a swath, picking up the fingers of the pick-up 9, the swath rises, combed and falls on the harvester 8, here, together with the biomass, the grain separated from the panicles falls. The auger 7 located on the header 8 receives the biomass and directs the swath from the middle to the edges, the auger 7 actively processes the biomass, at the same time grain is released from the panicles, which, remaining inside the biomass, moves to the activator 6, and then the biomass flow enters the inclined chamber 3. Chain-slatted conveyor 4, and working bodies 5 specially installed on the bottom, continue to perform control actions on biomass, distributing it across the width and height of the feeder chamber 3, in the most uniform layer in the course of its movement by the conveyor 4. The impact of the conveyor slats 4, the working bodies 5 installed on the bottom of the inclined chamber contributes to the further separation of the grain from the panicles and rice, together with the biomass, falls on the rotating receiving beater 11 and on the concave 12 of the threshing drum 13.

The grain released, at the first stages of contacts with the mechanisms and devices of the first and second levels, moves along with the flow of biomass, hiding between the stems. In the control device of the third level – the inclined chamber, the grain remaining in the panicles continues to separate, and the grain located between the stems, under the influence of an oscillatory movement from the «microspring effect», is sifted (separated), through the stems, periodically weakened by the load and find themselves in the lower, close to the surface of the bottom inclined chamber layers.

Let's consider the structure of the biomass flow passing through the control device of three levels.

Biomass at the time of approach to the threshing drum is a uniform layer of stems, panicles and up to 23 % of freely separated grain distributed by 70...75 %. Freely released grain, compressed by stems, moves in the biomass flow, after passing through the inclined chamber – the control device of the third level, having got into the oscillatory mode from the microsprings, the bulk of the free grain seeps into the lower layer of the flow and enters the concave in the first zone – the zone of free threshing and is sifted without receiving the impact of the drum 13 and replenishes the amount of high-quality marketable grain (Fig. 3 highlighted in green).

Part of the free grain that has not passed through the concave in the zone of the free threshing mode due to clogging or incomplete peeling, together with the biomass, enters the middle part of the concave in the zone of the gentle threshing mode and is sieved under the active directional impact of the whips of the drum 13 (Fig. 3 highlighted in yellow).

The remaining part of free grain and grain in panicles enters the zone of hard threshing mode, where the biomass is finally finished threshing under the action of the gap between the concave 12 and drum 13, as well as under the active shock and squeeze effects of the drum 13 (highlighted in red in Fig. 3).

The use of devices in the technological scheme of rice grain combines that activate leveling effects on the biomass of a compacted swath, uneven in height and width, will intensify the sifting of grain through the TSD deck and reduce the torque on the threshing drum shaft, by reducing the load, increase the productivity and quality of the combine.

It should be noted that the versatility of the device since the same number of working bodies can be placed on the short and elongated zones of the bottom of the feeder house. The number of working bodies depends on: the number of conveyor bars of the feeder house of the rice harvester, passing along one track per one revolution of the conveyor belt, as well as on the accepted coefficient of rice biomass leveling. According to pre-patent No. 19509 for «Method for determining the biomass leveling coefficient and a device for its implementation» [14].

The general layout of the control device based on the feeder house of the rice harvester is given in accordance with Fig. 4.

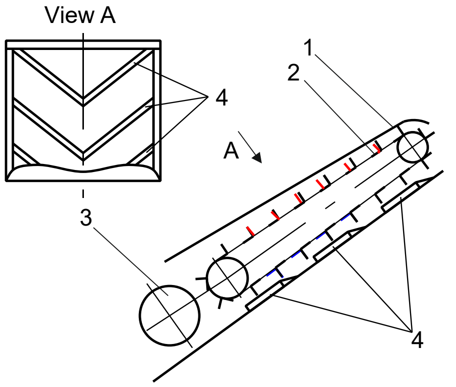


Fig. 4. The set of the control device of the inclined camera: 1 – inclined camera; 2 – conveyor; 3 – activator; 4 – working body of the control device

The control device in this form is an adapter, or an assembly unit, which is included in the combine kit for harvesting various grain crops [15, 16]. In the driving device, when the biomass is transported over the surface of the collection of working bodies, the redistribution of the stems with rice panicles that make up the flow, along the width, is activated. A series of collection of working bodies in the form of corrugations, located depending on the harvested crop, in a certain order on the bottom of the inclined chamber and is installed experimentally.

The main indicator or characteristic of the functionality of the controllers or adapters in rice harvesters is the pulling ability of the biomass controller «γ», determined by:

$$\gamma=\frac{t}{s}, \tag{1}$$

where γ is the pulling capacity of the biomass control device, sec/m^2; t – the total time of interaction of the working bodies of the driving devices with the biomass of rice, for one revolution of the feeder conveyor bars, sec; s – area, interaction of the working bodies of the control device, m^2.

The physical meaning of the pulling ability is the time of separation from the flow of an elementary layer from a unit area of the working body of naturally interconnected plants. It has been established that the efficiency of pulling apart biomass stalks depends on the operating modes of the harvester mechanisms and the parameters of the driving device.

The biomass entering the feeder house is distributed by a collection of working bodies, a conveyor and pressure devices.

The working bodies, represented by corrugations 4, in accordance with Fig. 4, view A, are placed on the bottom of the feeder house.

Thus, the biomass entering the shaping surface of the control device is actively redistributed and, along the guide edges of the working bodies, is moved by the conveyor 4 to the combine thresher.

The surfaces of the edges of the «*V*» – shaped profiles of the corrugations 4, on the bottom of the inclined chamber 1, direct the biomass of rice, along the depressions of the corrugations 4, displace it, simultaneously act on the panicles, with the edges of the corrugations 4, shift it from the middle of the inclined chamber 1, and facilitate movement along formed microcorridors, in a given direction.

The slatted conveyor 2 presses the biomass flow to intermittently spaced working bodies (corrugations) 4 and the bottom surface, activates its movement from the middle to the edges, and then directs it to the thresher of the rice grain harvester in an even layer in thickness.

The layout of the working bodies (corrugations) of the control device is shown in Fig. 5.

Since the upper part of the corrugations is made with a ledge towards the thresher, intermittent corrugations 2, with a gap equal to $\ell'=2\ell$, are placed depending on the yield and humidity of rice, with a high-yielding and highly moistened biological mass, with a gap equal to $\ell'=3\ell$.

The efficiency and operability of the control device in the presented design and technological design is determined using the methods of spatial modeling, which is theoretically substantiated and proved on the basis of the laws of mechanics.

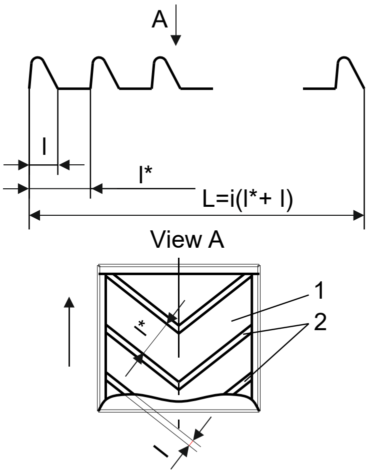


Fig. 5. Scheme of arrangement of working bodies (corrugations) of the control device: ↑ – direction of biomass movement; 1 – geometric surface; 2 – corrugated

Using the method of spatial modeling, two main geometric parameters that actively affect the heap of biomass and control the flow of the swath-the redistribution of stems with panicles in it are established and identified:

1. Angle «α» – the angle of installation of the working body towards the moving biomass, on the value, which depends on the activity of shifting the stems in the flow of the roll by the edge of the working body. An active shift of stems from the middle of the inclined chamber to its edges is observed, in the range $40° \le \alpha \le 50$, i. e. with a known value of the optimal angle of friction of the biomass against the edge of the working body $\varphi = 14...30°$.
2. The step of arrangement of the working bodies «ℓ» – their discontinuity among themselves, depends on the length of the feeder house of combines, a certain type and their number.

5. The results of the study of the work of the managing working bodies of the combine

5. 1. Construction of regression equations for the technological process

To study the mechanism of coordinated operation of all combine devices involved in leveling the rice swath, let's use the concept of a «black box» (Fig. 6). The system has an «input» for entering information about the adjustable parameters of the control device and an «output» for displaying the results of leveling the rice swath, characterized by optimization criteria.

The state of the output parameters Y presumably functionally depends on the state of the inputs X. The type of dependence $Y=f(X)$ is unknown and it can be established from the observed experimental data using the correlation-regression analysis [17–19].

The adjustable parameters $X_1, X_2, ..., X_k$, where k means their number in the experiment, are indicators characterizing the conditions for the process of leveling the rice swath, which can be controlled and purposefully change the course of the process in the direction we need.

Uncontrolled disturbances are random variables that affect the rice swath. There is no information about their physical nature of intensity and the nature of the change in time.

The output (resulting) parameters $Y_1, Y_2, ..., Y_m$ evaluate the quality of the process, characterizing the optimization parameters and economic indicators of the efficiency of rice swath leveling.

In a rice swath leveling experiment, the outputs are response functions to varying inputs. Each response function Y_s, $s=1, ..., 4$, depending on the input parameters $X_1, X_2, ..., X_k$ can be represented in general form as follows:

$$Y_s = f_s(X_1, X_2, ..., X_k),\ s=1, ..., 4. \quad (2)$$

The geometric representation of the response function (2) in the factor space $X1X2, ..., Xk$ is the response surface.

Since many interrelated qualitative and quantitative factors can be present in the mathematical description of the rice swath leveling process, in practice it is difficult to establish a universal objective function.

There are various ways to form a generalized objective function, and our task is to decide what constraints these responses and controlled variables should satisfy.

The target function can be the yield of commercial grain or the coefficient of leveling of the rice swath K_p, and the restrictions are the conditions that the controlled variables and adjustable parameters of the leveling process must be positive and satisfy certain technological restrictions.

Before the start of the experiment, the control device parameters $X_1, X_2, ..., X_k$ selected for optimization were coded, i. e. a linear transformation of the factor space was carried out. This greatly simplifies the study of the response surface and its regression equations obtained with respect to the coded variables $x_1, x_2, ..., x_k$.

The parameters and operating modes of the control device for leveling the rice swath and the selected levels of their variation are shown in Table 1.

Table 1

Rice swath leveling process parameters and their levels

Controlled parameters: coded (natural)	Coded levels				
	–α	–1	0	+1	α
x_1 – roll speed in the inclined chamber (v, m/s)	2.5	3	4	5	5.5
x_2 – roll height (h, mm)	–	22	27	32	–
x_3 – (a, degree) installation angle of working bodies (a, degree)	–	30	40	50	–
x_4 – spacing of working bodies (Δ, mm)	–	200	250	300	–

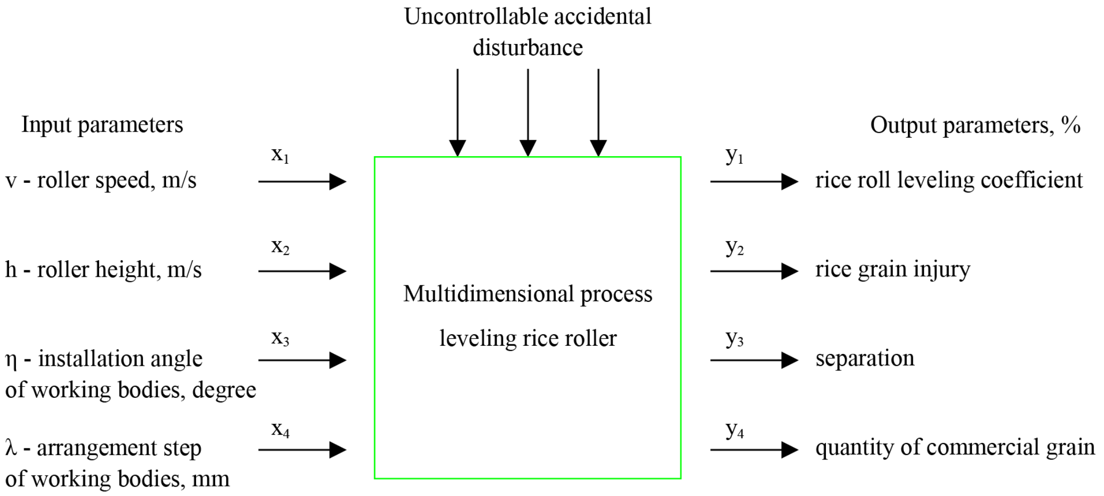


Fig. 6. Scheme of interaction between the parameters of rice swath leveling

All variables that determine the state of the rice roll, regardless of their physical and mechanical nature, can be divided as follows.

Input (independent) variables X_i, which are considered as the studied parameters of the control device of the rice swath:

- the speed of the roll in the inclined chamber υ_B, m/s;
- roll height h, cm;
- installation angle of working bodies α, deg;
- step of arrangement of working bodies Δ, mm.

The above parameters regulated in our experiment, according to the logic of preliminary studies on leveling the rice swath, affect the following dependent variables Y_s, which are taken as:

- Kp – rice swath leveling coefficient, %;
- T – rice grain injury, %;
- S_p – separation, %;
- M_t is the amount of marketable grain, %.

In accordance with the chosen plan obtained after randomization, the values of the output indicators were observed and recorded, according to which the regression equations were calculated, taken as objective functions:

– for the levelling coefficient of the rice roll (%):

$$K_p = Y_1\left(a_1,\ldots,a_m; x_1,..,x_k\right) \to \max; \tag{3}$$

– for traumatization of rice grains (%):

$$T = Y_2\left(\beta_1,\ldots,\beta_m; x_1,\ldots,x_k\right) \to \min; \tag{4}$$

– for separation (%):

$$S_p = Y_3\left(\gamma_1\ldots,\gamma_m; x_1\ldots,x_k\right) \to \max; \tag{5}$$

– the amount of marketable grain (%):

$$M_t = Y_4\left(\delta_1\ldots,\delta_m; x_1\ldots,x_k\right) \to \max. \tag{6}$$

In the STATISTICA 7.0 program (Model→Analysis of a Central Composite (Response Surface) Experiment – Model→Analysis of the central compositional experiment) using the least squares method (LSM), LSM estimates of b – coefficients for coded variables x_i ($i=1,\ldots,4$), their standard errors, Student's t-test for checking the significance of regression components, probability levels p, upper and lower 90 % confidence boundaries (Table 2).

The reliability and quality of the approximation of the obtained regression dependencies (3)–(6) were checked by the coefficients of multiple correlation R and determination R^2, the presence of serial correlation in the regression residuals was checked by the Darbin-Watson criterion d [7, 20]. The listed criteria calculated from the experimental data of rice roll leveling are given in Table 3.

As follows from (3)–(6), justification of the parameters of the rice swath leveling control device is a multi-purpose problem of nonlinear mathematical programming with the following restrictions on the area of the factor space:

$$x_{i\min} \le x_i \le x_{i\max},\ i=1,\ \ldots,\ k, \tag{7}$$

here $x_{i\min}$, $x_{i\max}$ – bilateral restrictions on the main parameters of the rice swath leveling control device.

In general, a model of multi-purpose optimization of the main parameters of the control device for leveling a swath of rice (3)–(6) is proposed, which belongs to the class of mathematical programming problems.

The extremum (maximum or minimum) of the above objective functions K_p, T, S_p and M_t was determined by canonical transformation of the quadratic response functions [21, 22].

Using the statistical data listed in Table 4, let's characterize all three replications of the available experimental data on leveling the rice swath: the position of the average, its scattering (scatter) and asymmetry.

Table 2

Results of multivariate regression analysis of indicators characterizing the process of rice windrow flattening

Factor	Regression coefficient	Standard error	Student's t-test	p-significance level	90 % confidence limits	
					lower	upper
1	2	3	4	5	6	7
Rice roll leveling coefficient $K_p=Y_1$, %						
–	78.96783	0.721698	109.4194	0.005818	74.41120	83.52445
x_1	2.08111	0.475683	4.3750	0.143056	–0.92223	5.08446
x_1^2	–3.37229	0.329893	–10.2224	0.062080	–5.45516	–1.28943
x_2	–3.71627	0.475683	–7.8125	0.081047	–6.71962	–0.71293
x_2^2	–3.10713	0.329893	–9.4186	0.067340	–5.18999	–1.02426
x_3	2.23330	0.306147	7.2949	0.086729	0.30037	4.16624
x_3^2	–3.47836	0.329893	–10.5439	0.060198	–5.56122	–1.39550
x_4	2.14057	0.475683	4.5000	0.139209	–0.86277	5.14392
x_4^2	–4.04405	0.329893	–12.2586	0.051818	–6.12691	–1.96118
x_1x_2	1.12807	0.621510	1.8151	0.320583	–2.79598	5.05213
x_1x_3	0.06250	0.400000	0.1563	0.901326	–2.46300	2.58800
x_1x_4	2.32123	0.621510	3.7348	0.166549	–1.60283	6.24528
x_2x_3	2.61250	0.400000	6.5313	0.096722	0.08700	5.13800
x_2x_4	2.06861	0.621510	3.3284	0.185809	–1.85544	5.99267
x_3x_4	0.56250	0.400000	1.4063	0.393523	–1.96300	3.08800

Continuation of Table 2

1	2	3	4	5	6	7
Percentage of injured rice grain $T=Y_2$, %						
–	20.29714	0.045106	449.986	0.001415	20.01235	20.58193
x_1	–2.14057	0.029730	–72.000	0.008841	–2.32828	–1.95286
x_1^2	2.03399	0.020618	98.650	0.006453	1.90381	2.16417
x_2	3.92438	0.029730	132.000	0.004823	3.73667	4.11209
x_2^2	2.14006	0.020618	103.794	0.006133	2.00988	2.27024
x_3	–3.19985	0.019134	–167.232	0.003807	–3.32066	–3.07904
x_3^2	1.92793	0.020618	93.505	0.006808	1.79775	2.05810
x_4	–2.61626	0.029730	–88.000	0.007234	–2.80396	–2.42855
x_4^2	2.77645	0.020618	134.660	0.004728	2.64627	2.90663
x_1x_2	–1.67876	0.038844	–43.217	0.014728	–1.92401	–1.43350
x_1x_3	–0.06250	0.025000	–2.500	0.242238	–0.22034	0.09534
x_1x_4	–3.13812	0.038844	–80.787	0.007880	–3.38337	–2.89286
x_2x_3	–4.48750	0.025000	–179.500	0.003547	–4.64534	–4.32966
x_2x_4	–2.42807	0.038844	–62.508	0.010184	–2.67333	–2.18282
x_3x_4	–0.23750	0.025000	–9.500	0.066767	–0.39534	–0.07966
Separation $S_p=Y_3$, %						
–	83.63732	2.210202	37.84149	0.016819	69.6827	97.59198
x_1	1.90273	1.456779	1.30612	0.415984	–7.2950	11.10047
x_1^2	–5.00675	1.010298	–4.95572	0.126759	–11.3855	1.37202
x_2	–3.71627	1.456779	–2.55102	0.237835	–12.9140	5.48147
x_2^2	–4.21126	1.010298	–4.16833	0.149895	–10.5900	2.16751
x_3	1.28373	0.937574	1.36920	0.401584	–4.6359	7.20334
x_3^2	–5.23656	1.010298	–5.18319	0.121333	–11.6153	1.14221
x_4	1.72435	1.456779	1.18367	0.446578	–7.4734	10.92209
x_4^2	–5.64315	1.010298	–5.58563	0.112780	–12.0219	0.73562
x_1x_2	0.53685	1.903373	0.28205	0.824987	–11.4806	12.55428
x_1x_3	0.16250	1.225000	0.13265	0.916041	–7.5718	7.89685
x_1x_4	1.59623	1.903373	0.83863	0.555731	-10.4212	13.61365
x_2x_3	0.98750	1.225000	0.80612	0.568077	–6.7468	8.72185
x_2x_4	1.44023	1.903373	0.75667	0.587624	–10.5772	13.45766
x_3x_4	0.78750	1.225000	0.64286	0.636275	–6.9468	8.52185
Quantity of marketable grain $M_t=Y_4$, %						
–	31.66909	0.451062	70.2101	0.009067	28.82120	34.51699
x_1	3.03248	0.297302	10.2000	0.062215	1.15539	4.90957
x_1^2	–3.28348	0.206183	–15.9250	0.039924	–4.58527	–1.98169
x_2	–3.95411	0.297302	–13.3000	0.047776	–5.83120	–2.07702
x_2^2	–2.87689	0.206183	–13.9531	0.045548	–4.17868	–1.57510
x_3	2.29287	0.191342	11.9831	0.053003	1.08479	3.50096
x_3^2	–3.30116	0.206183	–16.0108	0.039710	–4.60295	–1.99937
x_4	2.76491	0.297302	9.3000	0.068192	0.88782	4.64200
x_4^2	–3.61935	0.206183	–17.5541	0.036227	–4.92114	–2.31756
x_1x_2	1.37741	0.388443	3.5460	0.174989	–1.07513	3.82994
x_1x_3	0.03750	0.250000	0.1500	0.905214	–1.54094	1.61594
x_1x_4	1.28339	0.388443	3.3039	0.187106	–1.16915	3.73592
x_2x_3	1.43750	0.250000	5.7500	0.109620	–0.14094	3.01594
x_2x_4	2.91998	0.388443	7.5171	0.084195	0.46744	5.37251
x_3x_4	1.06250	0.250000	4.2500	0.147117	–0.51594	2.64094

Table 3

Statistical estimates of the quality of regression equations for rice roll leveling indicators

Criterion for assessing the quality of the regression equation	The value of the criterion			
	K_p	T	S_p	M_t
Multiple correlation R	0.931	0.974	0.864	0.890
Coefficient of determination R^2	0.866	0.949	0.747	0.791
The Darbin-Watson criterion d	0.555	1.914	0.440	0.481

The standard errors of the output indicators are small and are less than 10 % of the corresponding average values. There is an approximate equality of the mean, mode and median for the leveling coefficient of the rice swath K_p and the amount of commercial grain M_t.

At the same time, the values of kurtosis and asymmetry do not exceed 2 in absolute value; the minimum and maximum values are approximately equidistant from the average, the coefficients of variation do not exceed 33 %, with the exception of the M_t index (35.5 %).

This indicates the similarity of the empirical distributions with the normal, logarithmically normal, or generalized normal distribution law.

The main statistical characteristics of the output indicators of rice swath leveling are shown in Table 4.

Table 4

The main statistical characteristics of the output indicators of the leveling of the rice swath

Statistical characteristics	Conventions	Output indicators			
		$K_p = Y_1$	$T = Y_2$	$S_p = Y_3$	$M_t = Y_4$
Volume of observations (experiments)	N	18	18	18	18
Arithmetic mean	M	68.34	27.03	68.39	21.74
Standard error	m	1.82	1.85	2.16	1.82
Standard error, % of M m	m, %	2.67	6.85	3.16	8.36
Median	*med*	68.3	24.8	65.9	22.3
Fashion	*mod*	61.0	–	–	22.3
Standard deviation	s	7.740	7.859	9.176	7.717
Sample variance	s^2	59.906	61.769	84.203	59.545
Kurtosis	E	–0.220	0.949	1.688	–0.627
Asymmetry	A	0.134	1.260	1.395	0.397
Span	R	28.2	26.6	32.5	24.6
Minimum	min	55.0	18.9	59.3	12.0
Maximum	max	83.2	45.5	91.8	36.6
Coefficient of variation	V	11.3	29.1	13.4	35.5

The main prerequisites for the successful application of regression methods in modeling the process of leveling a rice swath are that:

– for each fixed value of the arguments $x_1, x_2, ..., x_k$, the dependent variable Y (the response function) is normally distributed with a normal distribution density function:

$$T = Y_2\left(\beta_1,\ldots,\beta_m;x_1,\ldots,x_k\right)\rightarrow \min,$$

$$\varphi(x) = N(\mu,\delta) = \frac{1}{\sqrt{2\pi\delta}}\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\delta}\right)\right], \tag{8}$$

where μ the parameters μ – arithmetic mean and Δ – standard are estimated according to the experimental data of the rice swath leveling process;

– the average value $M\{Y\}$ of Y is a function of $x_1, x_2, ..., x_k$:

$$Y = f\left(\beta_1,\ldots,\beta_m;x_1,\ldots,x_k\right), \tag{9}$$

containing unknown parameters $\beta_1, ..., \beta_m$. The type of this function is known, and the function is linear with respect to the parameters $\beta_1, ..., \beta_m$.

Analyzing the scatter plots and the relationship between the output indicators of the rice swath leveling process and the factors influencing them, in many cases made it possible to reveal their non-linear nature with respect to the controlled parameters of the control device.

The equations of quadratic regression depending on the speed of the rice roll in the inclined chamber x_1, the height of the roll x_2, the installation angle x_3 and the spacing of the working bodies x_4 are as follows:

– for the leveling coefficient of the rice swath K_p (%):

$$\begin{aligned}
&K_p = 78.97 + 2.08111x_1 - 3.37229x_1^2 - 3.71627x_2 -\\
&-3.10713x_2^2 + 2.2333x_3 - 3.47836x_3^2 +\\
&+2.14057x_4 - 4.04405x_4^2 + 1.12807x_1x_2 +\\
&+0.0625x_1x_3 + 2.32123x_1x_4 +\\
&+2.6125x_2x_3 + 2.06861x_2x_4 + 0.5625x_3x_4;
\end{aligned} \tag{10}$$

– for rice grain injury T (%):

$$\begin{aligned}
&T = 20.30 - 2.14057x_1 + 2.03399x_1^2 + 3.92438x_2 +\\
&+2.14006x_2^2 - 3.19985x_3 1 + 3.92793x_3^2 -\\
&-2.61626x_4 + 2.77645x_4^2 - 1.67876x_1x_2 -\\
&-0.0625x_1x_3 - 3.13812x_1x_4 -\\
&-4.4875x_2x_3 - 2.42807x_2x_4 - 0.2378x_3x_4;
\end{aligned} \tag{11}$$

– for separation S_p (%):

$$\begin{aligned}
&C_p = 83.64 + 1.90273x_1 - 5.00675x_1^2 - 3.71627x_2 -\\
&-4.21126x_2^2 + 1.28373x_3 - 5.23656x_3^2 +\\
&+1.72435x_4 - 5.64315x_4^2 + 0.53685x_1x_2 +\\
&+0.1625x_1x_3 + 1.59623x_1x_4 +\\
&+0.98750x_2x_3 + 1.44023x_2x_4 + 0.7875x_3x_4;
\end{aligned} \tag{12}$$

– for the amount of commercial grain M_t (%):

$$\begin{aligned}
&M_t = 31.67 + 3.03248x_1 - 3.28348x_1^2 - 3.95411x_2 -\\
&-2.87689x_2^2 + 2.29287x_3 - 3.30116x_3^2 +\\
&+2.76491x_4 - 3.61935x_4^2 + 1.37741x_1x_2 +\\
&+0.0375x_1x_3 + 1.28339x_1x_4 +\\
&+1.4375x_2x_3 + 2.91998x_2x_4 + 1.0625x_3x_4.
\end{aligned} \tag{13}$$

The solved regression equations (10)–(13) are a mathematical description of the relationship between the indicators of rice swath leveling K_p, T, S_p and M_T and independent factors – the speed of the rice swath in the feeder house x_1, the height of the swath x_2, the installation angle x_3 and the spacing of the working bodies x_4.

From the equations of quadratic regression of four controlled variables (10)–(13), the following conclusions can be drawn.

In all equations, the regression coefficients for linear terms and squares of the studied variables have opposite signs.

This indicates that the output indicators of the rice swath leveling process have an optimum [23].

Spatial (volumetric) graphs of Fig. 7 (e.g., sheet 1) give a visual representation of how the index K_p of leveling a roll of rice or the amount of commercial grain M_t is related to the roll speed in the inclined chamber x_1 and the height of the roll x_2 with the installation angle x_3 fixed at the main level and the placement step x_4 of the working bodies of the leveling device.

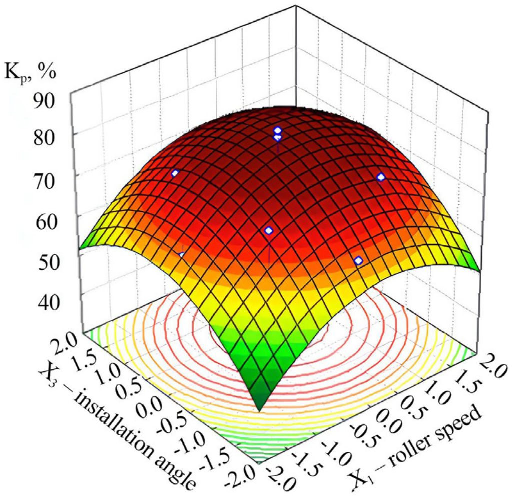


Fig. 7. Response K_p – rice roll leveling coefficient

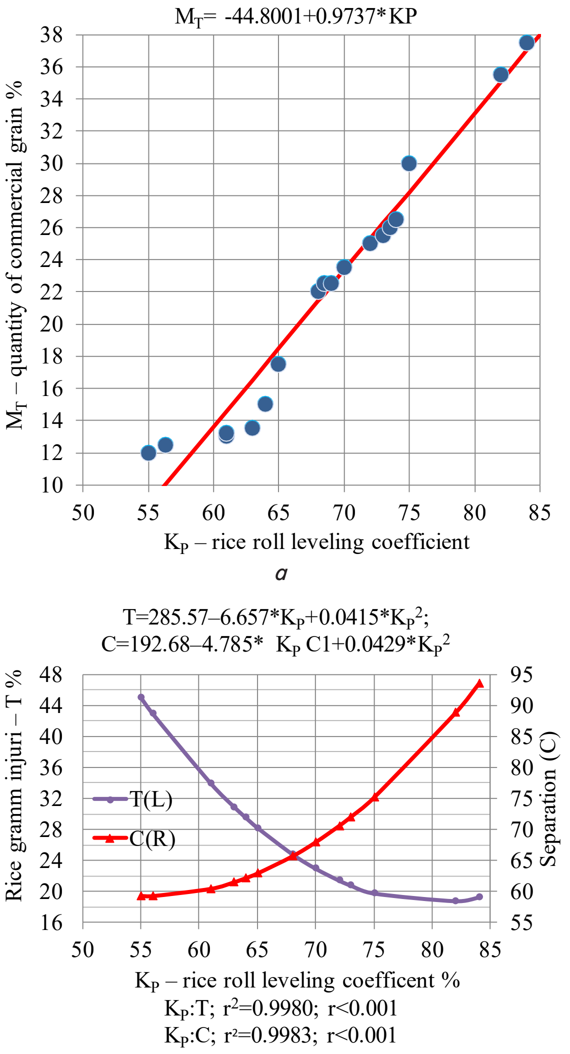
The color labels or shades of gray in Fig. 7 show, by means of intensity, the value of the rice roll leveling coefficient K_p or the amount of marketable grain M_t. They can be used to determine the range of values of variables x_1 and x_2, where K_p and M_t have the greatest value.

All pair interactions in regression equations (10), (12) and (13) are positive, and in (11) they are negative. This means that with an increase in any parameter of the screening device, there is also an increase in the leveling coefficient of the rice swath K_p, separation S_p and the amount of marketable grain M_t, while the injury of rice grain T due to negative pair interactions decreases.

Fig. 8 shows the results of solving the regression equation to determine the parameters and operating modes of the control device for leveling the rice roll.

As can be seen from Fig. 8, with an increase in the leveling coefficient of the rice swath K_p, the yield of marketable grain increases linearly and its injury rate decreases according to a quadratic law.

So, at K_p=75 %, the yield of marketable grain will be 28–30 % with an injury rate of 20 %.



a

b

Fig. 8. The relationship between the output indicators of the process of leveling the rice swath: *a* – regression coefficients with linear terms; *b* – coefficients for square variable parameters

5. 2. Determination the ranges of rational values of the design and technological parameters of the control device

Taking into account the revealed relationships between the output indicators of the rice roll leveling process and the result of canonical analysis and multi-purpose optimization, let's recommend the following parameters of the device leveling the rice roll:

– the speed of the roll in the inclined chamber υ=4.4 m/s;
– roll height h=24.9 cm;
– angle of installation of working bodies α=42.8 degrees;
– the pitch of the arrangement of the working bodies Δ=262.6 mm.

Let's believe that, with these parameters, the coefficient of leveling of the rice roll K_p will increase to 80.5 %, the injury rate of rice grain will decrease to 18 %, separation will be established at the level of 84.3 %, the yield of marketable grain will be 33.9 %.

The results of laboratory studies of the process of controlling the flow of rice biomass and the quality of its leveling showed that the main determining parameter is the supply [24, 25]. And not just the feed, but its value, the uniformity of the distribution of the layer across the width of the receiving chamber of the threshing machine, with the coefficient of unevenness k_{exp}=0.95...0.97 %.

The data obtained as a result of the experiments confirmed the theoretical assumptions about the relationship between the biomass leveling coefficient (k_{exp}) and the feed rate when using a biomass control device. It has been established that the leveling coefficient is proportional to the supply (q) of rice biomass and is inversely proportional to the product of biomass density in the roller, transport speed, width and height of the roller.

The leveling coefficient is determined by the formula:

$$k_{\exp} = \frac{q}{p} Bh\upsilon_t, \tag{14}$$

where k_{exp} – the coefficient of biomass leveling; q – the supply of rice biomass, kg/s; ρ – the biomass density of the rice roller, kg/cm^2; B – roller width, in the field, m; h – the height of the roller, m; υ_t – transportation speed, m/s.

Fig. 9 shows a graph of changes in the efficiency of the control device depending on the flow of rice biomass.

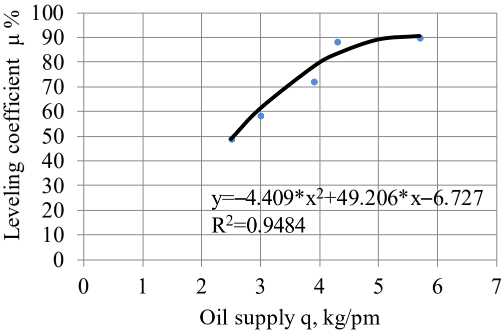


Fig. 9. Change in the efficiency of the control device depending on the supply (q)

It has been established that the coefficient k_{exp} characterizing the degree of leveling varies from the amount of feed entering the biomass feeder, in accordance with Fig. 9, with an increase in the feed of biomass, from 3.5 kg/line. meter, up to 5.5 kg/line. meter, the quality of the technological process improves, and the leveling of the biomass in the stream from 53 % increases to 88.7 %.

5. 3. The control device by the biomass flow of the rice harvester

Moving biomass in an inclined chamber, from above it was pressed by conveyor slats, and from below it contacted the surfaces of the control device – a collection of working organs installed in a certain order on the bottom. Stalks with rice panicles, moving on the surface of the working bodies, are forced under their influence to redistribute the cross-section of the flow, leveling its width, and due to the different sizes of the installation of working bodies in height and geometry, biomass, in the course of movement to the threshing and separating device additionally experienced periodically repeated shocks – vertical character, which contributed to the active separation of rice grains from the panicles to the threshing drum. Free grains, separated from brooms, clamped by stalks, under the influence of biomass oscillations, are released and penetrate into the lower layers of the flow. Moving as part of the flow, the grains of rice ready for separation, once in the TSD, sifted through the deck, independently, without the impact of the drum.

Experimental studies carried out in production conditions to assess the qualitative performance of the modernized combine have confirmed the effectiveness of the application of control devices, their impact on swath leveling and stabilization of the technological process of threshing.

The prototype of the control device installed in the improved inclined chamber was produced using a rice combine harvester, in accordance with Fig. 10, *a*, an upgraded combine harvester with a prototype, an improved inclined chamber, Fig. 10, *b* and with a removable set of working bodies representing the control device Fig. 10, *c*.

The study of the process of rice biomass flow control and quality of its leveling showed that the main, determining parameter is the feed. And not just feed, but its value, the uniformity of layer distribution over the width of the receiving chamber of the thresher, with the non-uniformity coefficient «k_{exp}»=0.95...0.97 %.

Fig. 11 shows a graph of changes in the distribution coefficient of rice biomass flow depending on humidity.

The implementation of the obtained regression equation, within the specified boundaries of variable factors, in accordance with Fig. 11, made it possible to graphically determine the dependence of the thickness of the rice biomass layer at the outlet of the biomass control device on these factors.

The results of experimental studies confirm the previously obtained theoretical assumptions about the need for uniform distribution of biomass across the width of the threshing chamber, stabilization of feed and speed of the combine harvester. It is possible to ensure the constancy of feed (q) by changing: cutting height, working width and speed of the rice grain harvester and the geometry of the control device's working bodies.


a *b* *c*

Fig. 10. General view of the upgraded rice combine harvester: *a* — upgraded rice combine harvester; *b* — inclined chamber with control device; *c* — removable set of control device

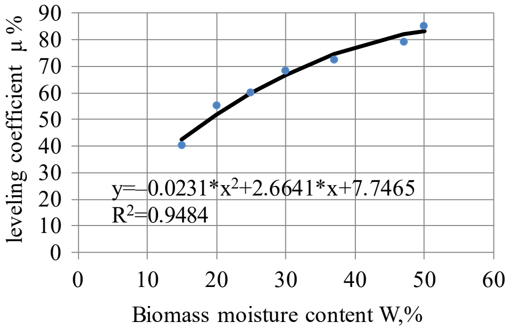


Fig. 11. Change in the leveling coefficient (μ, %) from the moisture content of rice biomass (*W*, %); at a constant supply (*q*)

Table 5 includes the main parameters and operating modes of the rice harveste.

Table 5

Optimal values of the parameters of the working bodies

Designation	Optimal modes and parameters
υ_r – feed rate of rice biomass, m/s	4.3
h_r – roll height, m	0.32
Δ – step placement of the corrugation, m	0.30
α – installation angle of working bodies, degree	43°

The extreme nature of the curves obtained as a result of laboratory studies made it possible to find the optimal modes and parameters of the working elements of the control device for the manufacture of a prototype of a removable kit, presented in Table 5.

The effectiveness of the impact on the biomass of the control device made it possible to justify a set of working bodies. When justifying the parameters of the working bodies, the test results are taken as a basis, and the established dependences of the technological and energy indicators of threshing, on the amount of rice biomass supply, and the regularities of their controllability. It has been experimentally proved that the technological parameters of the control device adapted in an inclined chamber, with a V-shaped profile and an angle of installation α=43°, of the working bodies give the best indicators for leveling.

6. Discussions of the technological process of threshing the combine

To improve the quality of the rice harvester, it is proposed to include additional innovative operations in the technological process of pre-threshing preparation of rice biomass with grain selection ahead of time, which increases grain separation, reduces injury, creates a stable mode of operation of the threshing and separating device of the combine.

The solution to the problem of ensuring a stable and uniform supply of the selected biomass to the threshing and separating device is an improved design of the inclined chamber. Equipped with a set of sets of working bodies, the inclined chamber of the combine has turned into an active control device for the incoming flow of biomass. Modified, according to our proposal, the geometry of the inclined chamber with working bodies, in a short period of time, the movement of a pile of biomass inside it, effectively affects the stems, panicles with rice – levels the layer and brings the biomass into oscillatory motion mode, i. e. promotes the active separation of ripe rice grains to the threshing drum.

The oscillatory nature (tossing) of the movement of biomass creates ideal conditions for passing through the stems, free grains of rice, to the bottom of the inclined chamber.

The principles of management of technological processes of cleaning are the main principles in management, arising from the emerging relationships of connections between the managed and controlling subsystems.

When monitoring the harvesting process, taking into account the analysis of control factors, their effects on the control parameters of the technological process of harvesting, it is necessary to establish the regularity of the correction of kinematic and technological modes. The adjustment of the modes during the technological process of harvesting is aimed primarily at influencing the flow of biomass coming from the picker into the inclined chamber further into the threshing machine with the help of control parameters, with the calculation of the maximum harvest of the productive part of the crop.

The program, for the development of innovative directions for the creation of multifunctional control devices of a rice combine harvester, provided for the development of experimental research programs that provide data on crop loss in various rice harvesting methods, their distribution to the main units of the combine – a picker, a screw, an inclined conveyor, a thresher.

The results of studies on evaluating the quality of work of the threshing and separating device of the modernized rice harvester under production conditions showed that with an increase in biomass moisture content from 20 % to 50 %, the leveling coefficient k_{exp} changes from 40 % to 88.7 %, with regard to increasing the speed of movement biomass from 2.0 m/s to 4 m/s, the efficiency of biomass leveling (k_{exp}) increases, and when it decreases to 1.5 m/s, unstable modes appear in the operation of the control device.

Further studies confirmed the conclusions that the main factors determining the efficiency of the rice harvester control device and its throughput are the feed (q) and kinematic parameters (the speed of the combine and feeder house conveyor).

The results of experimental research, confirm the previously obtained theoretical assumptions about the need for uniform distribution of biomass across the width of the receiving chamber of the threshing machine, stabilization of the feed, the speed of movement of the combine. It is possible to ensure a constant feed (q) by changing: cutting height, working width and speed of the rice harvester, as well as the geometry of the working elements of the control device.

The proposed innovative design of the feeder house, adapted to modern modifications of combine harvesters, equipped with a changing set (collection) of working bodies that create a surface geometry for control devices, moving along which a heap of biomass is evenly distributed over the entire width of the threshing drum, the feed is stabilized, the load on the drum is reduced. The «microspring effect» creates the conditions for the passage of the released free grains to the bottom of the inclined chamber and allows for the early picking of grains from the heap in the zone with insignificant drum impacts.

The developed modernized feeder house with a control device is installed on a rice harvester, which has passed production tests in the rice fields of the Experimental Agricultural Complex, Karatal district, Almaty region. Tests have established that the upgraded feeder house ensured consistently reliable operation of the rice harvester without overloads [26].

The method of rice biomass management during the harvesting process is a set of organizational and technological measures aimed at the comprehensive use of control factors and parameters of the combine, to reduce grain losses during threshing and reduce its injury.

In solving the problem of harvesting the maximum yield and minimizing grain injury, the emphasis is on increasing the control role of distribution devices.

Practical value in developing a collection of working surfaces and control devices that establish the relationship between structural and kinematic parameters and modes of the harvesting process, depending on the main factors (yield, rice variety; swath shape; feed q, kgp/m; degree of activation of biomass control k, %) etc.

Many researchers [24, 27, 28] note that modern rice-grain combines have serious disadvantages:

- passive controllability of the heap in the threshing zone (5–10 %);
- high sensitivity to uneven feed up to 38.6 %;
- increased humidity and strawiness of the crop mass (coefficient of variation of 41.2 %);
- significant damage and injury of grain up to 24.8 %;
- losses of under-ground and free grain, in the floor and straw coming off the straw stand up to 13 %.

The practical value of the study in the development of a collection of working bodies of control devices that establish the relationship between structural and kinematic parameters and modes of the harvesting process depending on the main factors (yield, rice variety; windrow shape; feed q, kgp/m; degree of activation of biomass control k, %.), etc.

The collection of working bodies of the biomass control device in accordance with the Fig. 10 is placed in the body of the inclined conveyor, on the bottom of profiles in the form of a corrugation (Fig. 10, *b*).

The disadvantages of this type of control device are:

- limited area of interaction of the beater comb with biological mass;
- low degree of flattening, pulling and leveling uneven flow of rice biomass when it is fed into the thresher harvester.

To eliminate above mentioned disadvantages, various options for constructive schemes of control devices are proposed, the working surface of which is made corrugated, moreover, the corrugations have a V or W-shaped profile, a slatted conveyor, and a drive.

The usage of a corrugated type of leveling device, when harvesting high-yielding and mixed rice biomass, leads to partial alignment of the biomass, due to the fact that the corrugation profiles on the bottom are located at the same distance from each other along the length of the inclined chamber of the rice harvester.

7. Conclusions

1. The regression equations mathematically describing the relationship between the indicators of rice swath leveling and independent factors (the inclined chamber, the height of the roll, the installation angle and the spacing of the working bodies) have been obtained and calculated, from which it can be seen that the output parameters of the process of rice swath leveling have optimum.

2. Based on the canonical analysis and multi-purpose optimization, the optimal parameters of the control device that leveled the rice swath in the pre-threshing period were established:

- the speed of the roll in the inclined chamber υ_B=4.4 m/s;
- roll height h=24.9 cm;
- installation angle of working bodies α=43 degrees;
- spacing of working bodies Δ=262.6 mm.

3. Justified a set of control device of working bodies on leveling of rice biomass adapted in an inclined chamber, with V-shaped profile and installation angle α=43°. It is established that the efficiency of swath leveling is proportional to the feed (q) of rice biomass and inversely proportional to the product of biomass density in the swath, transport speed (υ_r), swath width (B) and height (h_r).

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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