Criterial models of the stem separation process when harvesting rice

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Abstract. The problem of determining the influence of several major environmental factors on the value of grain losses during rice stem separation by a vibratory grain divider is considered. It makes it possible to establish the grain loss dependences upon varying the divider's parameters obtained for polynomial and criterial models, as well as enables to confirm the advantage and feasibility of using a vibratory grain divider on windrowers for rice harvesting. The criterion equations of the stem separation process by a vibratory grain divider are developed and the dependences of the change in the loss values behind the divider when cutting upright and lodged rice are obtained. They confirm the results of statistical studies, but to a greater extent illustrate information about the stem separation process. For this research, a classical theory of similarity and modeling was used, which made it possible to develop a model construction method taking into account physical and mechanical properties of plants when they are cut with windrowers on upright and lodged agricultural backgrounds with losses in the divider zone and under the windrow in the harvest field.

1 Introduction

It is known that combined active and passive dividers are used on windrowers for cutting rice, partially providing a reliable technological process of stem separation, which depends on the direction of stem lodging and the growing state of agricultural background [1-3]. Their work affects transportation of the cut mass into a windrow and its structure, and is accompanied by losses in the form of loose grain and cut off heads. These losses occur in the divider's zone and under the windrow at the site of its descent from the conveyor and make up a significant part of the losses that exceed agricultural requirements. At the same time, the uniformity of the windrow formation and its structure deteriorate, which also affects the operation of a threshing unit of the rice-harvesting combine, causing grain crushing and returns. Thus, there is a need to study the stem separation conditions to ensure the bond breaking between the lodged plants with minimal losses. The work tool implementing this is a two-stage vibratory grain divider, which is most effective when mowing rice, and works regardless of the stem lodging direction.

Analysis of the results obtained [1] shows that a vibratory divider is more effective in comparison with passive dividers of the sharp wedge and blunt wedge type, since the

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vibration impact on the stem allows to eliminate stagnant zones in the relative movement of the stems, to make better use of breaking the dissipative links between plants and does not allow the losses of cut-off heads.

To obtain reliable information after conducting laboratory studies, it was necessary to receive confirmation of its effectiveness in the field in comparative tests of serial machine dividers. For this purpose, a field research methodology was developed and a set of statistical information was produced, allowing for its processing to use second-order rotary designs with subsequent optimization of the regression equations' parameters.

The results of research [1] showed effectiveness of the chosen direction, however, this information does not allow to determine the relationship between optimal parameters of the vibratory grain divider and physical and mechanical properties of rice. Therefore, the study of stem separation by a vibratory grain divider and identification of objective regularities of this process is an urgent task.

2 Purpose and objectives of the study

The purpose of this study is to determine the influence of environmental factors on the amount of grain losses during rice stem separation by a vibratory grain divider when upright and lodged rice is cut with windrowers. The study considered the following environmental factors: plant hardness, yield, length, density, and connectivity.

To achieve the goal of the research it is necessary to solve the following tasks: 1) to develop a mathematical model of the grain loss process dynamics when the stems are divided by a vibratory divider, respectively, on upright and lodged rice; 2) to calculate the criterion equations' coefficients of the mathematical model; 3) to plot diagrams for criterion equations with subsequent analysis.

To build a mathematical model, we took the results of preliminary experimental studies of a vibratory grain divider in the form of grain loss regression models and the optimal operating parameters of a vibratory divider [4].

3 Research methods

The classical theory of similarity and dimension was taken as a research method [5]. To this end, using the research materials, as well as the equations of similarity and dimensions, a mathematical model was made up that showed the stem separation losses by a vibratory divider as a function of ten factors in the form of a criterial equation.

In order for the resulting model to be extended to similar conditions, it is necessary to fulfill all three similarity theorems, i.e. dependencies should be obtained as a set of functionally related complexes. Besides, according to the third similarity theorem the monovalency condition must be satisfied. In our case, it is ensured by using typical working bodies during experiments. According to the 1st similarity theorem, the equation should be monogenic, which is ensured by using equations containing homogeneous functions. Power functions have this property, therefore the equation is in the form of power complexes. Such an approach allowed to conduct a comparative assessment of the reliability of loss changes in the criteria and regression forms by way of polynomials.

4 Criterial modeling of process dynamics

Let us take as the basic units of dimension: length L_3, time T_3, angle Θ_3, mass F_3 [5]. We present a general equation in the following form

$$Q = \Phi(R, H, V_M, \beta, \omega, C, \gamma, P, EI, P_0), \tag{1}$$

where Q is the intensity of breaking bonds (accompanied by release of losses), F_3 / T_3; R is the radius of the eccentric of the drive mechanism L; H is the plant length, L_3; V_M is the speed of the machine, L_3 / T_3; β is the angle of inclination of the side faces of the divider in reference to the symmetry axis, Θ_3; ω is the rotational speed, Θ_3 / T_3; C is the crop yield, F_3 / L_3^2; γ is the upper cascade inclination angle, (Θ); P is the plant density, $1/L_3^2$; EI is the plant hardness, F_3 / L_3^2; P_0 is the cohesive properties of plants, F_3.

To find the criterial equation of losses when separating the stems with a vibratory divider, let us use the similarity theory and modeling methods [5,6].

$$Q = K_3 R^{x'} H^{y'} V^{z'} \beta^{\delta'} \omega^{\Delta'} C^{n'} \gamma^{m'} P^{k'} EI^{l'} P_0^{f'} \tag{2}$$

After substituting the dimensions into (2) we have

$$\frac{F_3}{T_3} = K_3 L_3^{x'} L_3^{y'} \left(\frac{L_3}{T_3}\right)^{z'} \Theta_3^{\delta'} \left(\frac{\Theta_3}{T_3}\right)^{\Delta'} \left(\frac{F_3}{L_3^2}\right)^{n'} \Theta_3^{m'} \left(\frac{1}{L_3^2}\right)^{k'} \left(\frac{F_3}{L_3^2}\right)^{l'} F_3^{f'} \tag{3}$$

In order for the equation to be homogeneous with respect to dimensions, the following relations between the exponents must be fulfilled:

$F_3 : 1 = n' + l' + f'$;

$L_3 : 0 = x' + y' + z' - 2n' - 2k' - 2l'$;

$\Theta_3 : 0 = \delta' + m' + \Delta$;

$T_3 : -1 = -z' - \Delta'$.

After the transformation we get

$$\frac{Q\beta}{H^2 \omega C} = K_3 \left(\frac{R}{H}\right)^{x'} \left(\frac{V_M \beta}{\omega H}\right)^{z'} \left(\frac{\gamma}{\beta}\right)^{m'} \left(\frac{EI}{CH^4}\right)^{l'} \left(\frac{PH^2}{EI}\right)^{f'} (PH^2)^{\Delta'}. \tag{4}$$

Equation (4) is the product of six dimensionless complexes and includes 10 independent arguments. After taking the logarithm of the specified equation, we get:

$$\ln \frac{Q\beta}{H^2 \omega C} = \ln K_3 + x' \ln\left(\frac{R}{H}\right) + z' \ln\left(\frac{V_M \beta}{\omega H}\right) + m' \ln\left(\frac{\gamma}{\beta}\right) + l' \ln\left(\frac{EI}{CH^4}\right) + f' \ln\left(\frac{P_0 H^2}{EI}\right) + \Delta'\left(PH^2\right). \tag{5}$$

Let us adopt the following notation:

$$k' = X_1;\; x' = X_2;\; z' = X_3;\; m' = X_4;\; l' = X_5;\; f' = X_6;\; \Delta' = X_7.$$

Denoting

$$\frac{R}{H} = Z_1;\; \frac{V_M \beta}{\omega H} = Z_2;\; \frac{\gamma}{\beta} = Z_3;\; \frac{EI}{CH^4} = Z_4;\; \frac{P_0 H^2}{EI} = Z_5;\; PH^2 = Z_6;\; \frac{Q\beta}{H^2 \omega C} = Z_7 \tag{6}$$

and inserting the above notation in equation (5), we obtain:

$$\ln Z_7 = \ln X_1 + X_2 \ln Z_1 + X_3 \ln Z_2 + X_4 \ln Z_3 + X_5 \ln Z_4 + X_6 \ln Z_5 + X_7 \ln Z_6. \quad (7)$$

From equation (7) we find

$$Q = \left[\frac{e^{\ln x_1} + X_2 \ln Z_1 + X_3 \ln Z_2 + X_4 \ln Z_3 + X_5 \ln Z_4 + X_6 \ln Z_5 + X_7 \ln Z_6}{\beta} \right] H^2 \omega C. \quad (8)$$

To solve equation (8), a computer program was developed that allows to make tabulation of the original data and to find the necessary equation coefficients. The obtained criterial models of losses when separating the stems of, respectively, upright and lodged rice by a vibratory divider are as follows:

$$\frac{\beta Q}{H^2 \omega C} = e^{1,416} \left(\frac{R}{H} \right)^{0,387} \left(\frac{V_M \beta}{\omega H} \right)^{0,142} \left(\frac{\gamma}{\beta} \right)^{0,473} \left(\frac{EI}{CH^4} \right)^{0,56} \left(\frac{P_0 H^2}{EI} \right)^{0,230} \left(PH^2 \right)^{0,070} \quad (9)$$

$$\frac{\beta Q}{H^2 \omega C} = e^{-6,116} \left(\frac{R}{H} \right)^{0,403} \left(\frac{V_M \beta}{\omega H} \right)^{-0,127} \left(\frac{\gamma}{\beta} \right)^{0,235} \left(\frac{EI}{CH^4} \right)^{0,412} \left(\frac{P_0 H^2}{EI} \right)^{0,527} \left(PH^2 \right)^{-0,335} \quad (10)$$

According to the calculation results, the adequacy of the approximated function theoretical series in respect of the actual measurements of losses and their intensity was checked, which showed that the discrepancy between the theoretical and the experimental data on average for each of the experiment variants is 10-15%. To establish the adequacy of criterial loss models by polynomial models, formulas (9) and (10) were converted into the following equations:

$$Q = e^{1,416} R^{0,387} H^{-1,089} V_M{}^{0,142} \beta^{-1,33} \omega^{0,858} \gamma^{0,473} EI^{0,79} C^{0,44} P_0{}^{-0,23} p^{0,07}; \quad (11)$$

$$Q = e^{-6,116} R^{0,403} H^{0,46} V_M{}^{0,127} \beta^{-1,362} \omega^{1,127} \gamma^{0,235} EI^{-0,115} C^{0,588} P_0{}^{0,527} p^{0,335}; \quad (12)$$

After inserting the obtained coefficients, they were solved with fixed optimal values of the factors using a computer. During calculations according to equations (11), (12), the values of the factors corresponding to the initial data were successively inserted in them.

5 Calculation results

The obtained results allowed us to construct graphs (Fig. 1, 2) and conduct an analysis, which showed:

- the change in losses behind the vibratory divider when changing the radius of the drive mechanism's eccentric $R(L)$, the angular speed of eccentric's rotation ω (Θ_3 / T_3), the inclination of the upper cascade γ (Θ), the deviation of the side faces from the axis of symmetry β (Θ_3), the speed of the machine V_M (L_3 / T_3) correspond to the graphical dependencies obtained for polynomial models;
- with an increase in the plant length on upright rice, the losses in the divider zone are reduced. It is explained by the fact that plant heads come out of contact with the upper cascade of the divider, which has a larger vibration amplitude in comparison with the lower part of the divider. Interaction of stems with the divider occurs in the lower parts of the plants, which leads to minimal losses;
- with an increase in the length of lodged plants, the losses in the divider zone increase, which is explained by the presence of large external friction between the stems and by great

entanglement of plants, i.e. it is necessary to expend more effort to pull out stem tufts from the entangled mass. Besides, the lower part of the divider is not sufficient for separating the stems. In this case separation occurs in the upper cascade of the divider;

- with an increase in yield, the losses in the divider zone for upright and lodged rice increase, which is explained by a large grain content of the head. An increase in losses in comparison with lodged plants is characteristic of upright rice with a change in the same variables, which is explained by a greater maturity of the head by the time of mowing in comparison with lodged rice;
- with an increase in plant stiffness of upright rice, the losses increase dramatically, which is explained by the impact of the divider on the stem of large diameter, which, due to its properties, provides a small amount of damping. The reduction of losses is characteristic of the lodged plant stand, since a stiffer stem is prone to lower lodging. When interacting with the divider, due to their elastic properties, the stems are separated better, since some pressing of the plants to the surface of the divider is provided and its effect on the plants is perceived with a smaller delay;

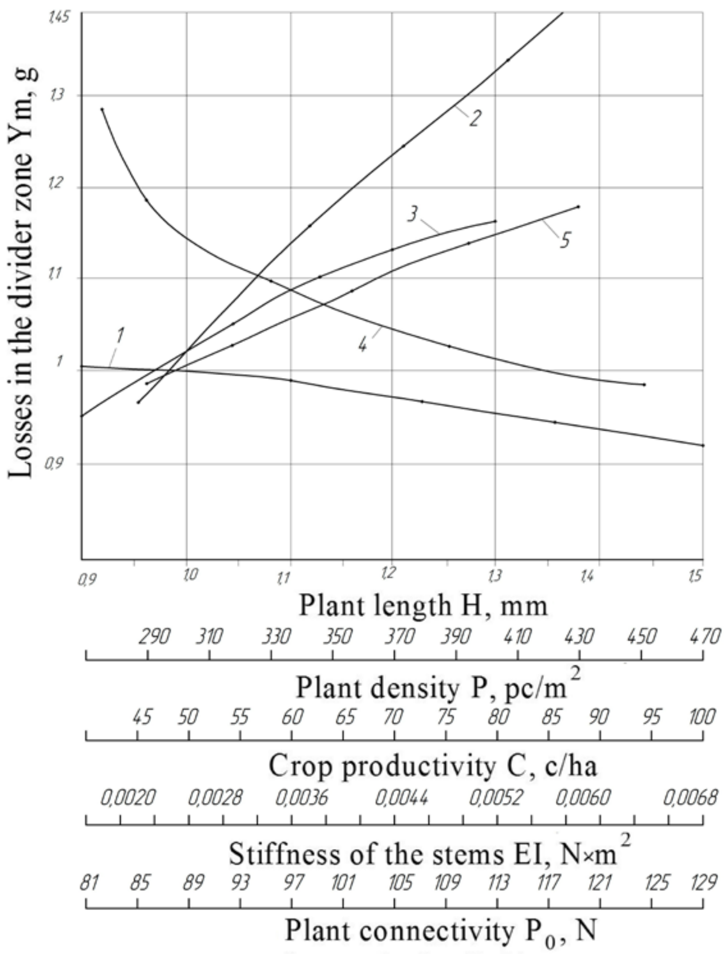

Fig. 1. Changes in losses behind the vibratory divider when mowing lodged rice by a triple-flow windrower depending on: 1 – plant density; 2 – crop productivity; 3 – plant length; 4 – stiffness of stems; 5 – plant connectivity.

- the losses are reduced with an increase in connectivity of upright rice, which can be explained by the fact that the impact of the working body on the stems is made on some vibratory system, which damps the blows. On the lodged rice plant stand, the losses increase with the increase in the plant connectivity. Plant heads directly contact with the surface of the divider; therefore, it is advisable to divide the stems on large sections of the divider's surface;
- with an increase in the stem density of an upright plant stand, an increase in losses was found as a result of a greater likelihood of the plant stand with a head getting onto the vibrating surface of the divider. These losses are lower for lodged rice, as the medium has a high density, which interacts better with the divider and is separated with a minimum seal. In this case, the conditions for the stem density increase, accompanied by the occurrence of stagnant zones when the stems are moved, practically do not arise.

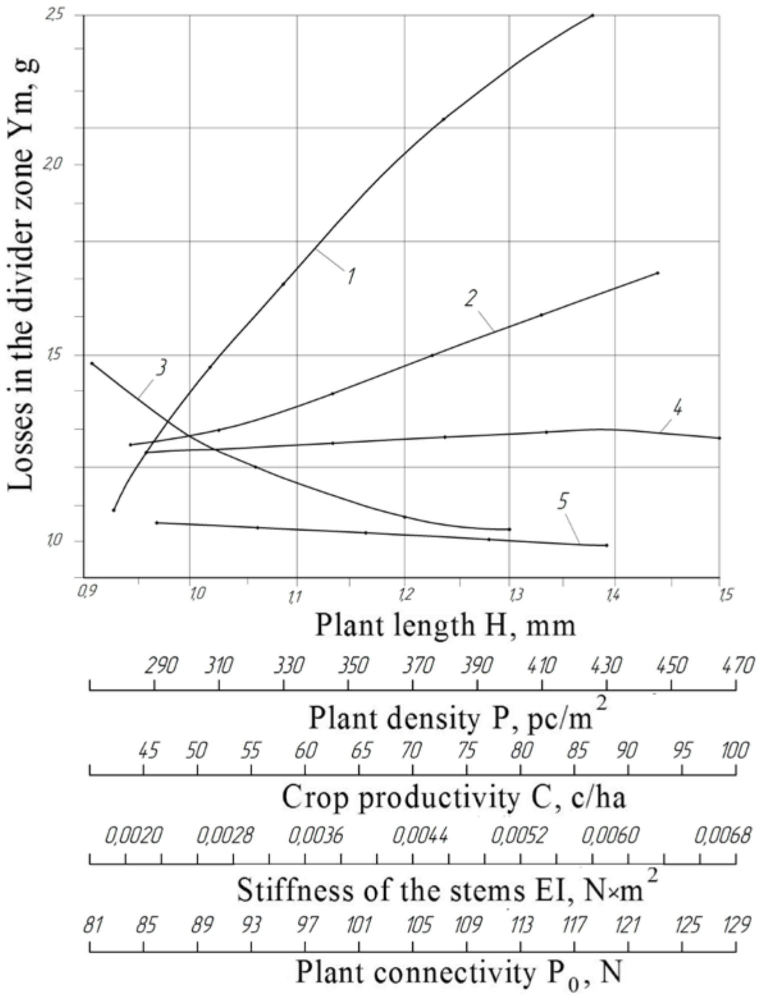

Fig. 2. Changes in losses behind the vibratory divider when mowing upright rice by a triple-flow windrower depending on: 1 –plant density; 2 – crop productivity; 3 – plant length; 4 – stiffness of stems; 5 – plant connectivity

6 Conclusion

As a result of the undertaken study based on a set of statistical information for various rice varieties and having used a classical theory of similarity and dimensions, the criterial models of stem separation were developed. They show that these models are close to the regression models and are a basis for the development of optimal recommendations on the use of dividers of this type in different rice-growing regions of Russia on various agricultural backgrounds.

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