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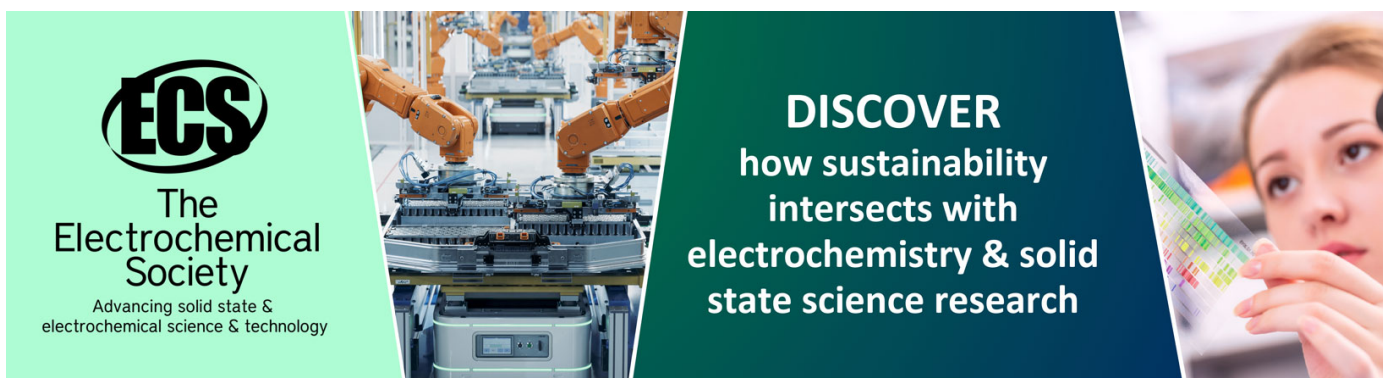
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Development of a method to control threshing process based on properties of harvested crop variety and external factors

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Abstract. The purpose of research is to determine how force of grain binding with the ear of winter wheat depend on properties of grain, its stage of ripeness and weather conditions. Objects of research is to consider dependences and regularities of changes in force of grain binding with an ear of winter wheat due to its temperature and humidity, duration of plant growing (standing) upon reaching full ripeness, ambient temperature and to assess the possibility of their use to control threshing process. Field experiments were carried out to determine force of grain binding with the ear of winter wheat of variety "Admiral", its temperature and humidity, ambient temperature, duration of plant growing (standing) after reaching full ripeness over the recommended agro-harvesting period. On the example of graphic dependence of parameters under discussion for the studied variety on duration of plant growing (standing) over the period of experiments we revealed the tendency of their change. Type and closeness of binding were assessed according to correlation and regression analysis. It is established that the correlation between force of grain binding with the ear of winter wheat and independent variables is linear. The analysis of regression equation parameters: overall coefficients of correlation, determination, values of the Fisher criterion, significance level, as well as the Durbin-Watson criterion ensured that the chosen model is adequate and can be applied in practice to control threshing process.

1. Introduction

Studies carried out by several authors show that micro-damage is one of the main ways of grain damage; reaching values from 10 to 40%, when harvesting grain crops by commercially produced and operated combine harvesters of various types and modifications [1; 2; 3]. Grain damage occurs not only during harvesting, but also during transporting and unloading operations, grain cleaning [4]. During storage fungi can penetrate in the damaged grain; as part of their life process they produce aflatoxins, that are virulent poison. Damage to seed grain also leads to a sharp decrease in its germination ability [5; 6]. At the same time, large grains of wheat are damaged mostly.

When threshing grain crops, the degree of micro-damage to grain depends on value of the impact and dynamic friction developed by threshing and separating device of a harvester, as well as on force of grain binding with inflorescence and its elastic properties [7]. For threshing the plants without damage to grain, impact or impulse or (and) force of dynamic friction should be greater than force of grain binding with the inflorescence, but smaller than the force, limited by elastic properties (elastic limit) of the grain being separated. In specific conditions of the harvest period, one of the reasons for the presence of crushed and micro-damaged grain in the bin storage may be the proximity of



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numerical values of its force of binding with the inflorescence, strength and elastic limit, as well as high degree of their variation due to heterogeneity of the grains within the field and even within one inflorescence [8]. The need to take into account complex properties of grain in the production of bakery products is shown in [9]. With this approach, one can most fully consider and respond to their specifics when developing the designed production process.

Grain deformation, which can be elastic, residual (plastic) and viscoplastic, mainly depends on humidity. At low humidity, elastic deformation prevails, residual deformation and viscoplastic one are almost imperceptible. Viscoplastic deformation increases with increasing humidity.

Thus, to ensure minimum micro-damage of grain of a particular variety in crop-specific weather conditions, during periods of end stage of wax ripeness and at full ripeness, when it should undergo threshing, it is important to have information about value of force providing grain separation from wheat ear, limit of its elasticity and strength. Unfortunately, there is no information on force of grain binding with inflorescence and elastic properties, in particular on its elasticity limit for different crops, and especially their varieties according to harvesting conditions. Meanwhile, as follows from the publications [10], for one type of culture, wheat, the value of force required to thresh the grain, there are three groups:

- varieties shattering, withstanding from 2.3 to 4.4 N;
- varieties non-shattering, withstanding from 5.2 to 7.3 N;
- varieties with tight threshing withstanding 12.8 N and more.

The numerical values of forces in all groups vary significantly with changes in humidity and temperature.

Force of grain binding with inflorescence is the most important characteristic of threshed plants. As it is shown in [11] it depends on the type of culture, its variety, degree of ripeness, duration of plant growing (standing) in the stage of full ripeness, ambient temperature and grain humidity. However, it is not given for characteristics of already being created and currently cultivated varieties. It is advisable to collect necessary data on its dynamics taking into account varietal characteristics as well as weather and climatic conditions during creation of the variety. This period is enough to obtain the necessary information about their impact on dynamics of force of grain binding with the wheat ear by the time of grain variety transfer into production. Obviously, with the improvement of breeding methods soon, it will be possible to create varieties with predetermined characteristics.

2. Materials and methods

Research and tests at the Institute for study of physical and mechanical characteristics of winter wheat, the most widely cultivated crop in the southern region of Russia, were caused by the need to obtain information to develop methods for designing promising processes and means of threshing the crops. They resulted in obtaining information on changes in characteristics of grain standing within the field, dynamics in biological losses of grain, some results are given in works [12; 13]. Further research development in this direction continued in 2018. The paper [11] presents the methods and results of field experiments on determining force of grain separation from the ear of winter wheat of rigid variety "Admiral" and easily threshed variety "Luchezar". It shows graphic dependences of changes in force of grain separation from the ear, air temperature, grain temperature and its humidity by day, obtained during measurements in the daytime.

3. Results and Discussion

Below, there are the results of studies on influence of air temperature and grain temperature, its humidity, duration of plant growing (standing) over the period of full ripeness on force of grain separation from the ear on the example of hard-to-thresh variety "Admiral". The experiments were conducted in the morning, afternoon and evening from June 21 to July 7 daily, and the following days until July 14, to determine the trend. The experience determined 108 values of force of grain separation from the ear, for twelve plants at the bottom, middle and top part of the ear during triple analysis. Ambient temperature was measured by the thermometer, and temperature of the grain and its humidity

content by device "Wile 65". Measurements were made in the field on a specially created movable unit. Stem part of wheat ear was attached to the tripod, equipped with a sensor measuring the force transmitted to the computer. Grain was separated from the wheat ear by the operator, grabbing with tweezers and then applying a force close to static. The range of force of grain separation from the ear was 0 - 26 N. In the range of 0 - 5 N measured force of grain separation from the ear was 63.4%, in the range of 5 - 10 N – 29.2%, and in the range of 10 - 15 N – 6.7%. In the range from 15 - 26 N measured force was 0.7%.

Figure 1 shows graphic dependence of changes in the average and maximum values of force of grain separation from the ear, its temperature and humidity, ambient temperature throughout the measurement period.

Obtained maximum values of force of grain separation from the ear are subject to change under the influence of precipitation, which is confirmed by the measurement data in the morning and afternoon of June 25, July 2 - 3 and July 6.

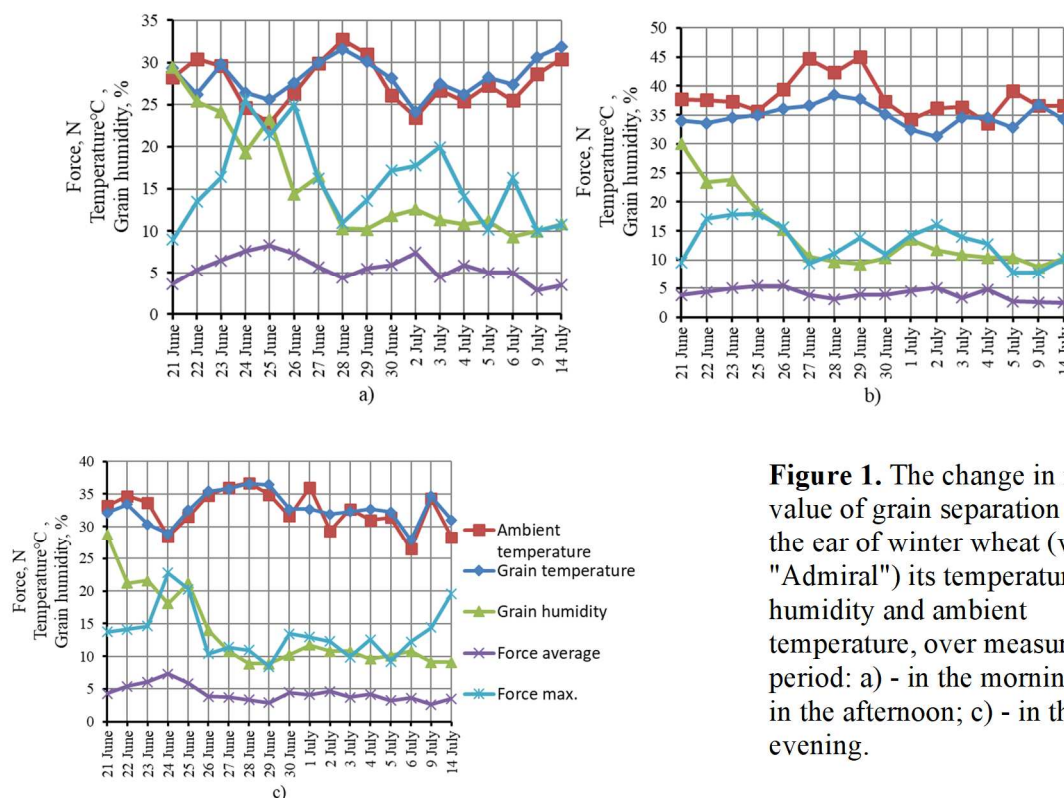


Figure 1. The change in force value of grain separation from the ear of winter wheat (variety "Admiral") its temperature, humidity and ambient temperature, over measurement period: a) - in the morning; b) – in the afternoon; c) - in the evening.

As can be seen in Figure 1, the average value of grain separation from the ear varies in the range of 2 - 8 N, and before full ripeness is opposite to grain humidity, but with full ripeness and before the completion of measurements, force of grain separation from the ear and humidity decrease.

Comparison of the values of graphic dependence shown in Figure 1 (a, b, c) confirms the conclusion about influence of grain temperature and grain humidity on the force value of grain separation from the ear. Its high values during the day fall on the morning hours, as during the night there is a decrease in air temperature, grain temperature and, therefore, humidity increases.

The maximum value of force of grain separation from the ear, obtained during the experiment on duration of plants growing (standing) differs 2 - 4 times from the average value of force of grain separation from the ear. So, at full ripeness on June 26, when grain humidity during the day fluctuated

within the limits of 13-15%, the maximum value of force of grain separation from the ear differed 2 - 3 times from its average value.

General tendency of change in force of grain separation from the ear over research period, is prevalently close to change in humidity of grain, its temperature, as well as ambient temperature. Thus, after a period of time corresponding to the completion of wax ripeness and at full ripeness, from June 26, there is a direct relationship between grain humidity and force of grain separation from the ear and the opposite one, between the separation force, temperature of grain and of the environment. Some changes in the trend were made by precipitation that fell on July 1, July 6, and from July 9 to July 14, which indicates the necessity of conducting experiments under different weather conditions (drought, average, wet weather conditions). It should be noted that the intensity and duration of precipitation were small. Precipitation did not lead to a significant increase in grain humidity, but it was sufficient for the increase in chaff humidity and force of its separation from the ear, which is reflected in the graph.

The change in force of grain separation from the ear depends on the duration of plant growing (standing) from the moment they reach full ripeness, with the increase in which there are biological losses of grain, including shattering. This trend is better displayed on the graphic dependence of the average value of force of grain separation from the ear, the numerical value of which was 8 N in the morning of June 25, and July 13 as well as 14 July it was 3 N.

As can be seen from the above dependence diagrams between the average value of force of grain separation from the ear and independent factors: grain humidity, its temperature, ambient temperature, the duration of plants growing (standing) at the time of measurement, there is a probabilistic relationship. The task to minimize micro-damage of grain during threshing a particular variety of harvested culture by operational control of the mode of combined harvester threshing device can be successfully implemented if the dependence between force of grain separating from the ear and listed independent variables is strong. In this study, it is required to focus on the model and present the regression equation in such a way that the predicted values of the average forces of grain separation from the ear, obtained by substituting the data of independent factors obtained in real time using sensors installed on the harvester, can be as close as possible to the real ones. That is, the difference between initial and predicted values should be minimal. Correlation and regression analysis involved selection of the model, checking the correlation between independent variables, and estimation of normality of data distribution for the average value of force of grain separation from the ear. Statistical processing of force of grain separation from the ear, tightness and form of its connection with independent variables were determined using software package "Statistica", version 13. Processing material includes experiments conducted between June 26 - July 14, except for skipped days due to rain.

The Kolmogorov-Smirnov test of force of grain separation from the ear, the number of measurements of which in each experiment was 108, showed compliance with the normal distribution. Due to the obtained result we can conclude that maximum force by approximated average values can be calculated based on the law of normal distribution.

For the analysis we use designations of variables:

X1 – grain temperature $^{\circ}\text{C}$;

X2 – ambient temperature $^{\circ}\text{C}$;

X3 – grain humidity %;

X4 – duration of plant growing (standing) from the moment of full ripeness, h.

Y – force of grain separation from the ear, N.

Table 1 shows statistical characteristics of measured values, as well as values of correlation coefficients, showing both the relationship of independent variables and each independent variable with the studied one.

Table 1. Statistical characteristics of studied factors and values of correlation coefficients between them

	X₂	X₃	Y	X₁	X₄
X₂	1.00	-0.16	-0.52	0.90	-0.28
X₃	-0.16	1.00	0.60	-0.28	-0.50
Y	-0.52	0.60	1.00	-0.66	-0.45
X₁	0.90	-0.28	-0.66	1.00	-0.19
X₄	-0.28	-0.50	-0.45	-0.19	1.00

As can be seen from the above data, the correlation between studied variable and each of independent variables is significant. Between grain temperature and ambient temperature the correlation is high, which indicates multicollinearity. According to the theory of statistics, if there is a strong correlation (greater than 0.85) between predictors, one of the factors should be excluded, according to the level of their significance, otherwise the overall regression model may be distorted. But analysis of their nature shows that the rate of their change is different. Grain temperature reaches values close to ambient temperature with a delay. Therefore, the exclusion of this factor may not be correctly displayed on the regression model. It was also taken into account that instruments and the process of measuring numerical values of these factors will be slightly different from those used in the experiments. According to evaluation of the parameters, in addition to ambient temperature, grain humidity is also an insignificant factor (significance level p is greater than 0.05), but the exclusion of these two factors noticeable affects overall adequacy of the model, estimated by the determination coefficient. Table 2 presents values of regression model parameters and their estimation.

Table 2. Regression model parameters and their estimation

Designation	Coefficient at regression equation (b)	Student's (t-test) criterion t (32)	Significance level (p)
Term	11.933	6.897	0.000
X ₂	-0.002	-0.046	0.964
X ₃	0.107	1.502	0.143
X ₁	-0.241	-3.620	0.001
X ₄	-0.006	-4.817	0.000

As table shows, variables X₂ and X₃ were insignificant. When excluding these variables, the values of correlation and determination coefficients changed slightly.

Table 3. Regression model summary table

	Values (2 factors)	Values (4 factors)
R	0.88	0.89
R₂	0.77	0.79
F (table / fact)	2.4/56.98	4.32/29.27
p	1.39*10⁻¹⁰	2.75*10⁻¹⁰
d	1.58	1.61

In this regard, it was decided to leave all the factors in the regression equation as follows.

$$Y = 11.933 - 0.002X_2 + 0.107X_3 - 0.241X_1 - 0.006X_4 \quad (1)$$

From this regression equation, in natural form, it can be concluded that change in ambient temperature, grain humidity, grain temperature, duration of plant growing (standing) by one unit, results in a change in optimization parameter, on average, by 0.002, 0.107, 0.241, 0.006 units, respectively. The difference in small coefficient in regression equation of duration of plant growing

(standing) and the highest level of its value in comparison with other factors is caused by too large difference in dimensions of factors.

According to analysis of parameters of regression equation, overall correlation coefficients (R), determination (R^2), values of the Fisher criterion (F), significance level (p), and the Durbin-Watson criterion (b), the chosen model is adequate and can be applied in practice.

Figure 2 shows a scattering diagram of predicted values (X -axis) and non-standardized residuals (Y -axis). The diagram also shows the upper and lower confidence intervals. This graph is used to test the assumption that relationship between independent variables and dependent variable is linear.

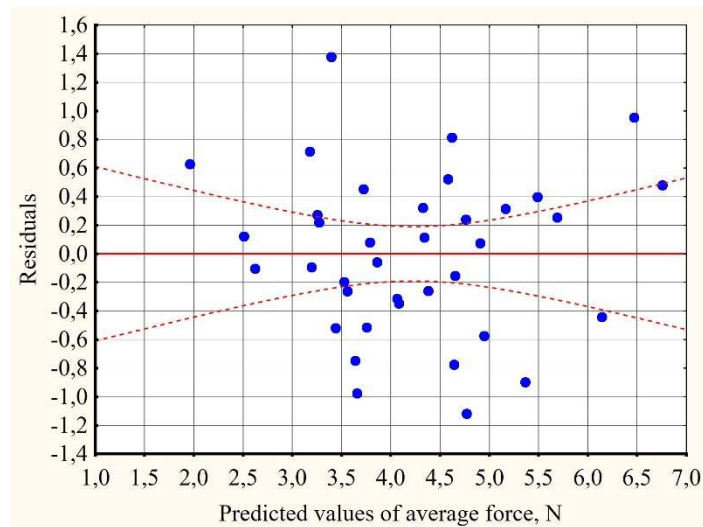


Figure 2. Scattering diagram of predicted values of force relative to zero line of residuals.

In our case, we can see that the points of residuals are evenly spaced relative to zero line. Based on the above, we can conclude that the resulting model is adequate and can be applied in practice.

Figure 3 shows a graph of the observed average values of force of grain separation from the ear and predicted by substituting into the resulting equation of regression model.

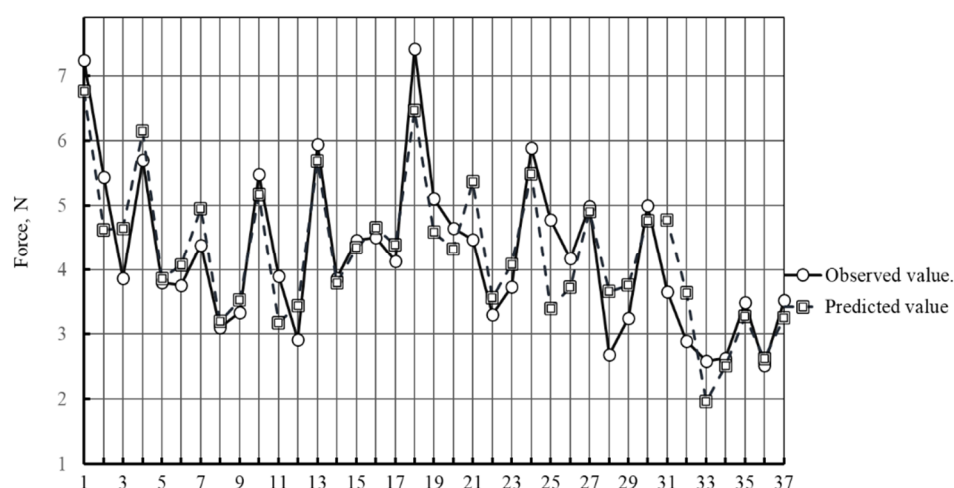


Figure 3. The graph of dependence of observed (continuous) in experiments average values of force of grain separation from the ear and predicted (dotted) by substitution in the resulting equation of regression model.

As can be seen from dependences presented in the graph, convergence between the obtained data of numerical values of force of grain separation from the ear and predicted ones is quite good. To exclude the under-threshing of ears, provided at the maximum values of force, we determine in accordance with the normal law of distribution: $Y_i = Y + 3S$. To calculate force impact on the inflorescence by mechanical devices or working body in the form of air jets, ultrasonic vibrations on the obtained values of force of grain separation from the ear, the classical theory of shock interaction between grain, inflorescence and working body will be applied [14; 15].

4. Conclusion

1. Force of grain binding with inflorescence is the most important characteristic of plants being threshed. It is advisable to collect necessary data on its dynamics according to varietal characteristics and weather and climatic conditions during creation of the variety. This period is sufficient to obtain necessary information about their impact on dynamics in force of grain binding with the wheat ear by the time of grain variety transfer into production.

2. The dependence between the average value of force of grain binding with the ear of winter wheat variety "Admiral", its humidity, temperature, ambient temperature and duration of plant growing (standing) after achieving full ripeness is characterized by regression equation $Y = 11.933 - 0.002X_2 + 0.107X_3 - 0.241X_1 - 0.006X_4$. Strength of the relationship between dependent variable and independent factors is estimated by multiple correlation coefficient $R = 0.89$ and determination coefficient $R^2 = 0.79$. Such a close relationship between studied factors makes it advisable to use it to create a method of operational management of threshing process.

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