THEORETICAL GROUNDING OF RATIONAL DESIGN FOR STRAW DISPERSER WORKING ELEMENTS OF GRAIN COMBINE HARVESTER
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ТЕОРЕТИЧЕСКОЕ ОБОСНОВАНИЕ РАЦИОНАЛЬНОЙ КОНСТРУКЦИИ РАБОЧИХ ОРГАНОВ ИЗМЕЛЬЧИТЕЛЯ-РАЗБРАСЫВАТЕЛЯ ЗЕРНОУБОРОЧНОГО КОМБАЙНА

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ABSTRACT
The article presents the theoretical description of the interaction process between the straw particle and guide plate concave surface of the deflector of grain combine harvester disperser. The equation of particle present velocity is obtained. It is proved that particle velocity decreases by 8,5% at plate radius reduction from 5 m to 4 m and by 15% when particle angle of attack changes from 25° to 50°. To decrease adverse effect of particle interaction with guide surface we suggest the usage of bladed choppers with slantwise set cast blade.

РЕЗЮМЕ
Выполнено теоретическое описание процесса взаимодействия соломистой частицы с вогнутой поверхностью направляющей пластины дефлектора измельчителя-разбрасывателя зерноуборочного комбайна. Получено уравнение текущей скорости частицы. Установлено, что скорость частицы снижается на 8,5% при уменьшении радиуса пластины с 5 м до 4 м, и на 15%, при уменьшении угла атаки частицы с 25° до 50°. Для снижения вредного влияния взаимодействия частиц с направляющей поверхностью, предложено использование лопастных ножей с косо установленной швырковой лопастью.

INTRODUCTION
One of the most important performance quality indicators of grain combine harvester straw disperser is the dispersion uniformity of tailings' grinded parts (T) along field surface *(Skorlyakov V.I., 2015; Skorlyakov V.I. et al, 2013; Yagelsky M.Yu. and Rodimtsev S.A., 2016)*.

According to agro technical requirements *(Yagelsky M.Yu. and Rodimtsev S.A., 2015; Cherkasov G.N. et al, 2013; Maslov G.G. and Trubilin E.I., 2016)*, non-uniformity of straw dispersion should be no more than 20%. However, field tests data demonstrate sufficient excess of the permitted indicators for some types of grain harvest machinery. Thus, some authors' investigations *(Lovchikov A.P. et al, 2016; Sadretdinov D.R., 2016; Yagelsky M.Yu. and Rodimtsev S.A., 2016)* proved that for grain combine harvesters of some brands, the variation coefficient of straw dispersion across the mowing width can be up to 75 % and more. Herewith maximum deviation from mean value M_{mean} reaches 137 %, causing the largest mean weight variation of shredded straw on the meter long distances from mean value.

For design solution development, which provides the improvement of shredded straw dispersion across the mowing width, it is necessary to analyse particle interaction of tailings with straw disperser working elements. The investigation targets were grounding the rational design of the tested device choppers.

MATERIAL AND METHODS
To carry out the investigations we used the improved design of straw disperser of grain combine harvester (fig. 1).

In the improved design of straw disperser, choppers are manufactured with blades are set to an angle α to chopper surface. Blades of the pair of choppers are located in a single surface, oriented from the rotor center to its periphery. Choppers pairs located in the center of the rotor have blade surfaces, which are symmetrical each other and oriented to rotor off-center.

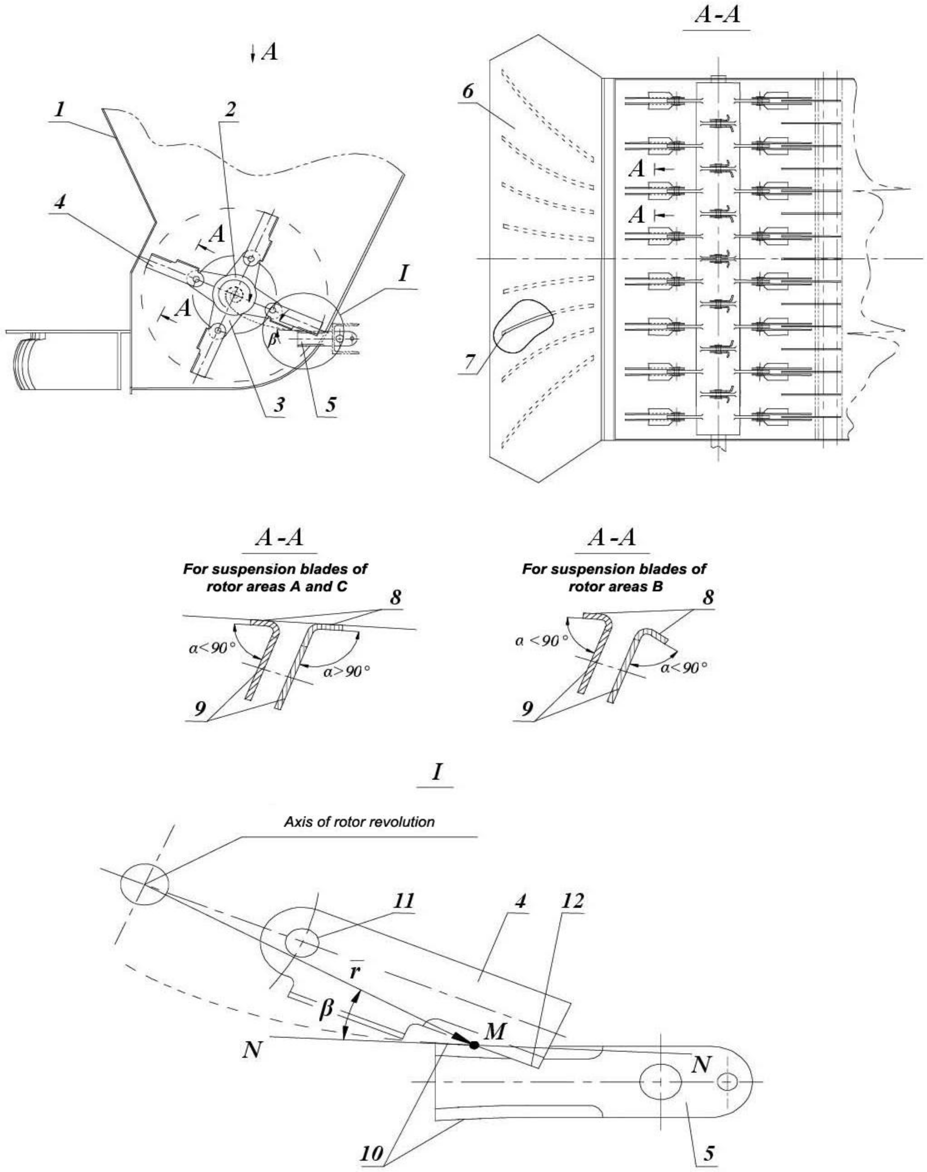

Fig. 1 - Improved design scheme of the straw disperser of grain combine harvester

1 – case; 2 – rotor; 3 – bracket; 4 – chopper; 5 – fixed counter blade of chopper; 6 – straw disperser; 7 – disperser guide plates; 8 – blades of pendular choppers; 9 – blade body; 10 – cutting edge of fixed counter blade; 11 – blade opening; 12 – chopper cutting edge

The increase of the cutting process efficiency and of straw disperser efficiency are achieved due to concave cutting edge *10* of fixed counter blades *5*, done in the form of logarithmic spiral, with pole located on rotor revolution axis *2*. Angle α of material pinching in cutting pair opening remains constant along the entire length of cutting edge *10* of fixed counter blade *5*. This provides equal kinematic cutting mode at the initial and final stages of the process. The extended length of the curved surface of cutting edge *10* of fixed counter blade *5* provides more complete usage of technological potential of the cutting pair.

The qualitative straw dispersion behind combine harvester is achieved by directed airflows, which are formed with blades *8* of pendular choppers *4*, their surface vectoring being directed sideway from rotor centre *2*. They, together with guide plates *7* of disperser *6*, provide uniform dispersion of the chopped mass in full bandwidth.

Usage of logarithmic spiral, with pole located on rotor revolution axis for concave cutting edge of fixed counter blade allows obtaining the next positive result. Because of the known property of logarithmic spiral, angle β between radius-vector $\bar{r}$, drawn from rotor revolution centre *2* to any point *M* on cutting edge line *10* of fixed counter blade *5* and tangent N-N to the line of cutting edge *10* at the same point, is the same.

Because of the radial position of longitudinal axis of chopper *4* towards the axis of rotor revolution *2* and its parallel position towards radius-vector $\bar{r}$, angle α of pinching between cutting edge *12* of chopper *4* and tangent to cutting edge *10* of fixed counter blade *5* at any point, will be the same too.

General view of the set of the experimental working elements for straw disperser of grain combine harvester "John Deere W650" is presented in fig. 2.

Fig. 2 - Set of experimental working elements for straw disperser of grain combine harvester "John Deere W650"

RESULTS

Theoretical analysis of interaction between the stem materials and the working elements of grain combine harvester disperser is carried out with application of known methods of theoretical mechanics, particularly – chapter “Differential equations of particle dynamics”.

Straw coming off the straw rack is captured with rotating vertically straw chopper rotor blades and is taken into the gap between counter cutting elements and then to the equipment bottom.

Being pinched in the opening of the cutting pair “blade - counter blade”, straw stems are chopped fast and having got kinetic energy increment at the account of impulse from the chopper working element linear velocity and impact of directed airflow, they are thrown into deflector opening. Falling on disperser guide plates, grinded particles of tailings change the path of original motion and get scattered throughout the field surface.

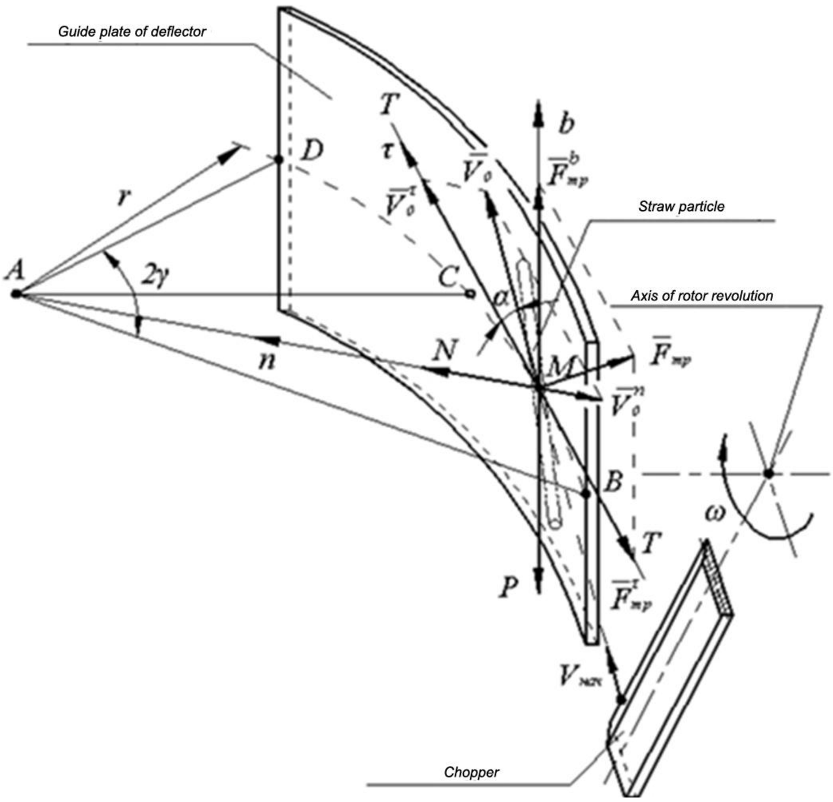

Fig. 3 - Scheme of velocity determination of particle motion along guide plate surface of disperser deflector

It is necessary to point out that, velocity vector $V_{initial}$ of tailings particles, coming from rotating rotor blades is directed perpendicular to its revolution axis. Thus, particle contact with curved surface of deflector's guide plate will be associated with velocity loss caused by the influence of sliding friction force, at particle movement along guiding line. Herewith particle energy losses will be higher the bigger the angle between particle velocity vector $V_{initial}$ and tangent guide plate at the point of initial contact.

Velocity reduction of particles coming off deflector guiding predetermines the reduction of their flying range and dispersion width and thus, increase the distribution non-uniformity.

To estimate in the first approximation the velocity change of particle at its relative movement along the concave surface of the guiding, we should examine the process of their interaction after particle coming off the rotating chopper (fig. 3).

To simplify the problem of studying the particle dynamic characteristics, some assumptions were admitted. Considering the particle as material point, because of its small mass and short duration of impact time, the energy input for particle deformation when reaching the guide plate was not taken into account. Particle velocity $V_{initial}$, at its coming off rotating blade was considered to be equal to the blade linear velocity and the initial velocity of particle V_0, on its reaching the guide plate:

$$V_{initial} = V_0 \tag{1}$$

Curvature radius of disperser guide plate was admitted constant (r=const) along the plate length. Solving the problem in the simplified position, airflows influence was not considered and it was assumed that maximum value of friction force did not exceed particle gravity force.

Point with mass *m,* gets on disperser guide plate, which is a part of cylindrical surface of radius *r*, with initial velocity V_0. Mutual disposition of vector V_0 and generating T-T guide plate at the contact point are determined by angle α.

In motion of the point along curved path, its velocity changes along the direction. Decomposing vector $\overline{V}_0$ into two constituents: $\overline{V}_0^{\tau}$ – directed along guiding (tangential velocity component $\overline{V}_0$) and $\overline{V}_0^{n}$ – directed perpendicular to guiding (normal velocity component $\overline{V}_0$), we obtain:

$$\overline{V}_0 = \overline{V}_0^{\tau} + \overline{V}_0^{n} \tag{2}$$

Models of velocity components $\overline{V}_0$ are equal correspondingly:

$$V_0^{\tau} = V_0 \cdot \cos\alpha \tag{3}$$

$$V_0^{n} = V_0 \cdot \sin\alpha \tag{4}$$

In the motion along the curved surface, the material point is affected by the following forces: gravity force $\overline{P}$, normal reaction of curved surface $\overline{N}$ and friction force $\overline{F}_{тр}$.

Obviously, gravity action $\overline{P}$ determines point shift vertically. Thus, sum vector $\overline{F}_{тр}$ of friction force will be formed by tangential component $\overline{F}_{тр}^{\tau}$ and binormal $\overline{F}_{тр}^{b}$, directed upward vertically:

$$\overline{F}_{тр} = \overline{F}_{тр}^{\tau} + \overline{F}_{тр}^{b} \tag{5}$$

Taking into consideration the assumptions made, the point moves along curved plate surface, formed by BCD circle arc, radius *r*, with central angle equal to *2γ*. At curvilinear motion of constrained point, it is easier to solve the problem in projection on an axis of true trihedral.

Differential equation of material point motion in projections on an axis of true trihedral is written as follows:

$$m\frac{dV_{\tau}}{dt} = \sum Fk_{\tau}\ ; \tag{6}$$

$$m\frac{V^2}{\rho} = \sum Fk_{n}\ ; \tag{7}$$

$$0 = \sum Fk_{b} \tag{8}$$

where:

V_{τ} – velocity projection on direction of tangent to the path;

$\overline{V}$ – velocity module:

ρ – radius of path curvature at the given point.

Fk_{τ}; Fk_{n}; Fk_{b} – projections of force F on the axis of true trihedral (τ – tangential; n – principal normal; b – binormal).

Since the analysis aim is determining the dependence of particle traverse velocity from applied forces impact, the given problem is referred to inverse dynamic problems of material point.

The second axiom or basic law of dynamics, belonging to Newton, establishes the dependence of particle acceleration $\overline{a}$ relatively inertial reference frame on the force affecting it (resultant force) $\overline{F}$ and mass *m* of point:

$$m\overline{a} = \sum_{k=1}^{n} \overline{F}_k \tag{9}$$

According to basic law of dynamics and superposition law (9), we obtain:

$$m\overline{a} = \overline{P} + \overline{F}_{тр}^{b} + \overline{F}_{тр}^{\tau} + \overline{N} \tag{10}$$

Using expressions (6-8), projecting vector equality (10) on axes of natural trihedral, we obtain

$$m\frac{dV}{dt} = -f \cdot N; \tag{11}$$

$$m\frac{V^2}{r} = N; \tag{12}$$

$$0 = +P - F_{тр}^{b} \tag{13}$$

Using (12), we obtain equation (11) in the form:

$$m\frac{dV}{dt} = -f \cdot m\frac{V^2}{r} \tag{14}$$

Reducing left and right parts of equation (14) by *m* and reducing variables, we obtain:

$$\frac{dV}{V^2} = -\frac{f}{r}dt \tag{15}$$

Integrating left and right parts of equation (15):

$$\int \frac{dV}{V^2} = -\frac{f}{r}\int dt \tag{16}$$

we obtain:

$$-\frac{1}{V} = -\frac{f}{r}t + C \tag{17}$$

Correlation (17) is the first integral of differential equation (14) of material point movement m on axis τ of natural trihedral.

To determine integration constant *C*, we substitute into equation (17) initial condition of movement (at $t = 0$, $V_0^{\tau} = V_0 \cdot \cos\alpha$), we obtain:

$$-\frac{1}{V_0 \cdot \cos\alpha} = -\frac{f}{r} \times 0 + C \tag{18}$$

From formula (18), integration constant value C:

$$C = -\frac{1}{V_0 \cdot \cos\alpha} \tag{19}$$

Then, expression (17) will be as follows:

$$-\frac{1}{V} = -\frac{f}{r}t - \frac{1}{V_0 \cdot \cos\alpha} \tag{20}$$

Converting (17), we obtain:

$$\frac{1}{V} = \frac{f \cdot t \cdot V_0 \cdot \cos\alpha + r}{r \cdot V_0 \cdot \cos\alpha} \tag{21}$$

Then, the equation of the current velocity of material point *M*, at its movement on guide plate of disperser deflector, is as follows:

$$V = \frac{r \cdot V_0 \cdot \cos\alpha}{f \cdot t \cdot V_0 \cdot \cos\alpha + r} \tag{22}$$

From expression (22) it follows that velocity of tailing particle, moving along the deflector plate, dcreases with the course of time being on the plate and with the decrease of concave surface radius.

The equation graphical form (22) demonstrates the decrease of particle current velocity by about 13%, at a contact time with the plate of 0.1 sec (fig. 4). Reduction of concave surface radius from 5 m to 4 m results in a decrease of particle movement velocity by 8,5%. Herewith, due to hyperbolic character of function *V(r)*, variation of guide plate curvature radius in its minimum values provides maximum degree of such dependence.

Therefore, it should be pointed out that the intensity of particle velocity decrease at the deflector contact with the plate is conditioned by angle *α* between velocity vector $\overline{V}_0$ and the guiding that generates surface T-T. For example, increase of angle of attack *α* from 0° to 25° (fig. 5), results in reduction of particle movement velocity by 4,2%; at changing *α* from 25° to 50°, particle movement velocity reduces almost by 15%.

Further increase of the angle between particle velocity vector and the guiding that generates the surface at the contact point causes the faster decrease of particle movement velocity.

The carried out analysis demonstrates negative influence of interaction of tailing particle and the deflector guiding plate on the parameters of its movement.

Those stated above allow to maintain that the reduction of negative influence of guiding plates can be achieved for example by changing the direction of tailing particles flight, after their coming off the chopper.

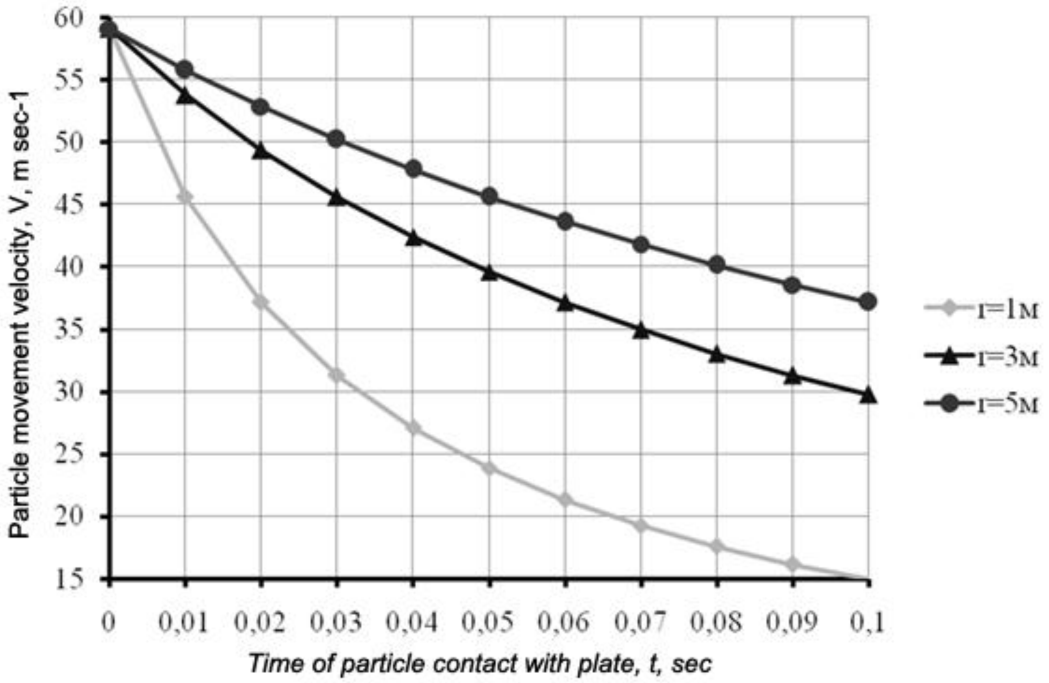

Fig 4 - Influence of radius (r) of deflector guiding curved surface and contact time (t) with straw particle, on its movement velocity (V)

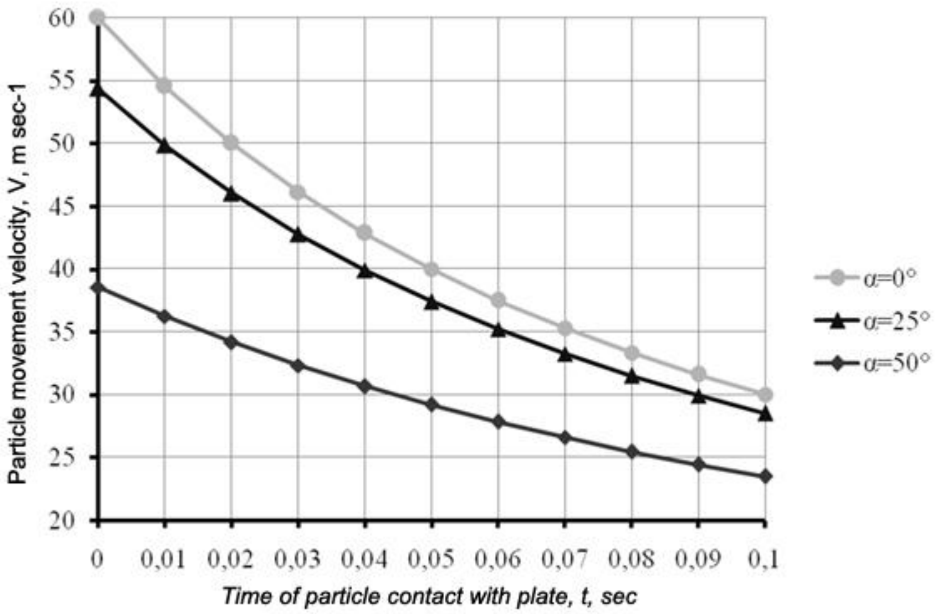

Fig. 5 - Dependence of straw particle movement velocity (V) on the contact time (t) with guide plate surface and attack angle (α), at the moment of the beginning of their interaction

The particle movement path from rotating blade to the periphery of disperse area (fig. 3), reduces the probability of interaction of chopped stems and the guiding, without decrease of quality of straw disperse on the field area. Therefore, the direction of particle flight, under some angle *β* to apical axis of combine harvester, reduces angle *α* between velocity vector $\overline{V}_0$ of the particle and generating T-T deflector guiding, at the contact point. This will also provide the decrease of negative influence of interaction between the guiding and the particle on its movement velocity. Thus, the conditions for increasing uniformity of straw dispersing along the field surface will be created.

Technically, the flight direction change of chopped tailing particles can be achieved by using blades that can combine this task with the main function– straw chopping.

Blades design with blades located perpendicular to choppers plane in its front part is known *(Sadretdinov D.R., 2016; Skorlyakov V.I. and Yurina T.A., 2016; Yagelsky M.Yu. and Rodimtsev S.A., 2017)*. This blade drawback is airflow formed by it, the direction of which as well as the path of chopped particle movement at coming off chopper blades are strictly parallel to combine harvester symmetry axis. This provides low degree of straw distribution uniformity across the width of disperse zone.

The suggested design of straw disperser chopper blades of grain combine harvester provides the following advantages:

- decrease of degree of chopped straw distribution non-uniformity without violation of cutting process kinematics;
- decrease of energy input for chopped straw dispersing at the account of formed powerful airflows with direct effect;
- the proposed technical solution does not cause serious design alterations, but its working elements enhancement is possible in the conditions of any machine work-shop and does not require some extra materials.

CONCLUSIONS

1. The expansibility of chopped straw dispersion width at the account of reducing the particle contact with deflector guide plate is theoretically substantiated. The equation of material point current velocity at its motion along the disperser deflector guide plate is obtained.

2. Based on the experimental data of the field investigations, we plotted diagrams of dependences of chopped particle movement velocity on duration of its contact with the deflector plate for different curve radii of the plate and attack angles at the beginning of the interaction between the particle and the plate.

3. To decrease adverse effect of interaction between straw particle and the surface of disperser deflector guide plate of grain combine harvester, the usage of bladed choppers with slantwise set cast blade is proposed.

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