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Mathematical modeling and research of the work of the grain combine harvester cleaning system

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ABSTRACT

The purpose of this study is a mathematical description of the structural and technological parameters of the air-sieve cleaning of the grain pile for the implementation of a simulation model of the technological process of the cleaning system of a grain combine harvester. The method is given for determining the coordinate of the nodal points of a sieve mill to calculate their speed of movement, as well as to study structural and technological parameters. As a result, the following were determined: the coordinates of the nodal points of the sieve mill of the cleaning system of the combine harvester, their speed and movement acceleration; a mathematical model of the operation of the sieve mill of the combine harvester cleaning system has been developed; the Froude number for the sieve mill Fr = 5.3 is the ratio between the forces of inertia and gravity, in the field of which movement occurs; experimental measurements of the speed of the air flow on the surface of the sieve mill for the existing structures of the cleaning system of modern combine harvesters amounted to 3.75 … 10.2 m / s, which are necessary for the implementation of mathematical models of a complete description of the technological process of cleaning system in the combine harvester using methods of two-phase flow mechanics.

1. Introduction

1.1. The problem statement

The technological process of separation of the grain pile from large impurities (spikelets, straw remnants, etc.) and light impurities (husks, small weed seeds, etc.) in combine harvesters (CH) occurs in the cleaning system by air-sieve. The existing air-sieve cleaning systems have a number of significant drawbacks as to the quality of the implementation of the technological process of separation of the grain pile from impurities. This is due to the increase in throughput, uneven ripening of the grain mass, unevenness of grain entering the cleaning, different concentrations of grain particles (grain and impurities), moisture and grain contamination, uneven distribution in width when harvesting on slopes. This is due to the unevenness or violation of the uniform distribution of the air flow over the entire area of the sieves due to the imperfection of the existing structures of the cleaning system, as well as the lack of a complete theoretical description and methods to substantiate their structural and technological parameters (Mudarisov et al., 2017; Badretdinov and Nasyrov, 2017; Badretdinov and Mudarisov, 2017; Miu, 2015; Spokas et al., 2016; Steponavičius et al., 2008; FAO Report, 2014; Feiffer et al., 2005; Kelemen et al., 2005; Kutzbach and Quick, 2001; CIGR; Miu and Kutzbach, 2007; Rademacher, 2003; Baran et al., 2016; Kundu and Gupta, 2014; Mudarisov and Badretdinov, 2013; Vasilevskij et al., 2013; Sorochenko and Mathematical, 2017; Sorochenko and Mathematical, 2016; Xu et al., 2019). In the CH cleaning system, the process of air-sieve separation of a grain pile from impurities can be mathematically described as a complex system of polydisperse two-phase flow, taking into account the forces of gravity, friction and inertia. One phase is the air flow generated by the fan, and the other is solid particles (elements of a grain pile). In this case, the particles can have: different concentrations and physicomechanical properties (mass, density, geometrical dimensions, humidity, elasticity, sailing, etc.). These phase differences determine the nature of the interaction between the air flow and the particles. The inertia and sailing of particles (heavy - seeds, light - chaff) lead to a different trajectory of their movement. The light particles are moved (separated) by the air flow due to the aerodynamic drag force, which exceeds the gravitational force, the cause of which is the difference between the air and particle velocities. The heavy particles are predominantly moved (separated from the light ones) by the force of gravity and inertia of sieves, while the aerodynamic resistance force

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acts slightly (Alferov, 1987; Kotov and Chaus, 2010; Mudarisov et al., 2017; Badretdinov and Nasyrov, 2017; Badretdinov and Mudarisov, 2017; Rademacher, 2003; Baran et al., 2016; Kundu and Gupta, 2014).

1.2. Research aims

The aim of this study is to substantiate the kinematic (constructive-technological) parameters of the sieve mill of a combine harvester to take into account the inertia force for the implementation of a mathematical model of the technological process of cleaning system in the combine harvester, taking into account its structural and technological parameters.

2. Materials and method

2.1. Research approach

For an accurate mathematical description of the technological process of the CH cleaning system, it is necessary to establish how the model takes into account the presence and intensity of interfacial interaction (particle relaxation time, Froude number), metabolic processes, particle concentrations, and so on. It is necessary to establish the "gas-particle" interaction mode (air-grain and air-impurities), which is determined by the Reynolds number of the particle Re_p and the volume concentration of the particles Φ, as well as the kinematic (structural-technological) parameter of the sieve mill to take into account the inertial force. In turn, to determine the data of these parameters, it is necessary to know the amount of the material entering the cleaning (capacity), the speed of the air flow and particles, as well as the coefficients of their aerodynamic resistance (Mudarisov et al., 2017; Badretdinov and Nasyrov, 2017; Badretdinov and Mudarisov, 2017; Miu, 2015). One of the most important functional parameters of the layer motion on the sieve surface is the Froude number, which expresses the ratio of forces acting on a particle lying on the sieve, the amplitude of sieve oscillations and gravity.

2.2. Mathematical model

Let us consider the design scheme for determining the coordinate of the nodal points of the sieve mill of the CH cleaning system for calculating their movement speed, inertial forces acting on the grain pile particles lying on the sieve (see Fig. 1).

Let $h_{k,x}$ and $b_{k,y}$ be the coordinates of the points O_k, $k = 1, 2, 3$. The point M_0 at the time t has coordinates

$$x_0 = R\cdot\cos\omega t, \quad y_0 = R\cdot\sin\omega t \tag{1}$$

Let us find the coordinates of points $M_1 - M_4$ according to the following algorithm:

(a) First we find the coordinates of the point M_1 from the conditions

$$\begin{cases} M_0M_1 = L_1, \\ O_1M_1 = L_2. \end{cases} \tag{2}$$

Note that in this case, depending on the parameters L_1, L_2, R, t, this system can have either two, or one, or not a single solution. We assume that the numbers L_1, L_2 and R are chosen so that for any t the system has a solution. Which of the two solutions to choose, we shall discuss below.

(b) Let us find the coordinates of the point M_2 according to the coordinates of the already found point M_1 from the system:

$$\begin{cases} M_1M_2 = L_3, \\ O_2M_2 = L_4. \end{cases} \tag{3}$$

In this case, the remark of the preceding paragraph regarding the existence of a solution and the choice of a unique solution is valid.

(c) Let us find the coordinates of the point M_3 on the found coordinates of the point M_1 as follows:

$$\vec{OM_3} = \vec{OM_1} + \frac{L_2 + L_5}{L_2}\vec{M_1O_1} \tag{4}$$

or by coordinates:

$$x_3 = x_1 - \frac{L_2 + L_5}{L_2}(x_1 - h_{1,x}) \tag{5}$$

$$y_3 = y_1 - \frac{L_2 + L_5}{L_2}y_1 \tag{6}$$

(d) Let us find the coordinates of the point M_4 by the found coordinates of the point M_3 as in point b) the coordinate of the point M_2 was found by the coordinates of the point M_1, that is, from the system:

$$\begin{cases} M_3M_4 = L_6, \\ O_3M_4 = L_7. \end{cases} \tag{7}$$

In points (a), (b) and (c) the following problem is solved: given the points F and G and the numbers l_1, l_2 we need to find the point $M\ (x;\ y)$ from the conditions

$$\begin{cases} FM = l_1, \\ GM = l_2. \end{cases} \tag{8}$$

Writing this system in the form

$$\begin{cases} FM^2 = l_1^2, \\ GM^2 = l_2^2. \end{cases} \tag{9}$$

Let's write it on the coordinates:

$$\begin{cases} (x - x_F)^2 + (y - y_F)^2 = l_1^2, \\ (x - x_G)^2 + (y - y_G)^2 = l_2^2. \end{cases} \tag{10}$$

Let us express y from the second equation:

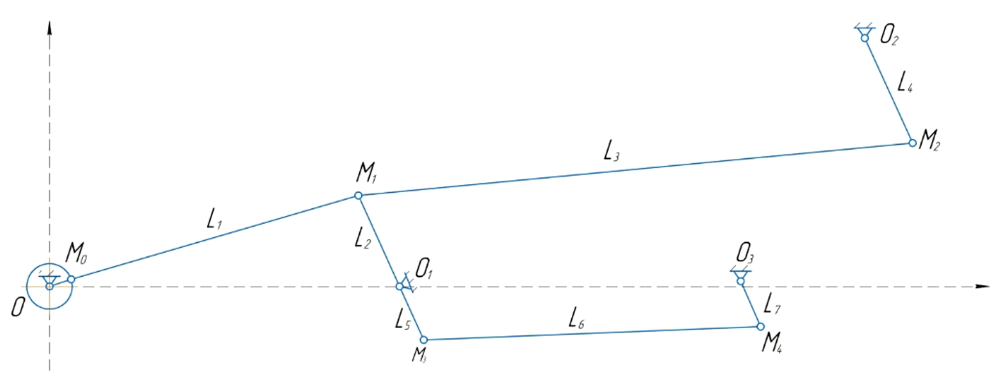


Fig. 1. The design scheme of the sieve mill CH cleaning system.

$$y = y_G \pm \sqrt{l_2^2 - (x - x_G)^2} \tag{11}$$

In this case, the " + " sign is taken before the root if it is known that the point M lies above the point G, and the sign " − " if it is below.

Substituting this expression in the first equations, we get:

$$(x - x_F)^2 + (y_G - y_F \pm \sqrt{l_2^2 - (x - x_F)^2})^2 = l_1^2 \tag{12}$$

Opening the brackets and getting rid of irrationality, we get a quadratic equation:

$$Ax^2 + Bx + C = 0 \tag{13}$$

where

$$A = 4a^2 + d, \tag{14}$$

$$B = -4a^2b + 4ac - 2x_G d, \tag{15}$$

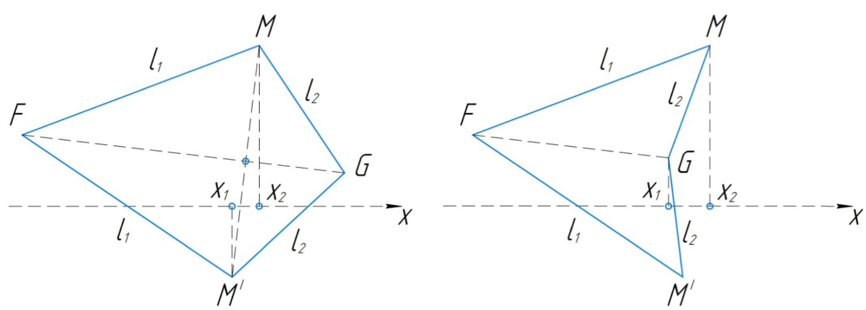
$$C = a^2b^2 + c^2 - d(l_2^2 - x_G^2) - 2abc, \tag{16}$$

$$a = x_G - x_F, \quad b = x_F + x_G, \quad y_F^2 + l_2^2 - l_1^2, \quad d = 4y_F^2, \tag{17}$$

If the discriminant $D = B^2 - 4AC$ is non-negative, then the equation has a solution. In the case of a positive discriminant, the question of choosing a root arises. Here the mutual arrangement of the points F and G is important. Three situations are possible:

(1) F lies above point G.

(a) $FG > max\{l_1, l_2\}$ (b) $FG < max\{l_1, l_2\}$



As we see, both in case (a) and in case (b), at the upper point M, the horizontal coordinate is larger than that of the lower M^I. Therefore, if due to some considerations, for example, structural ones, the upper point is obviously a solution, then the horizontal coordinate of the point M is calculated by the formula

$$x = \frac{-B + \sqrt{D}}{2A},$$

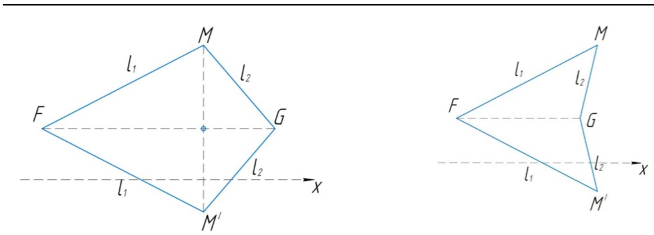
and if lower, then by the formula

$$x = \frac{-B - \sqrt{D}}{2A},$$

Let us notice, that $A = 4a^2 + d > 0$.

(2) F and G are at the same height.

(a) $FG > max\{l_1, l_2\}$ (b) $FG < max\{l_1, l_2\}$

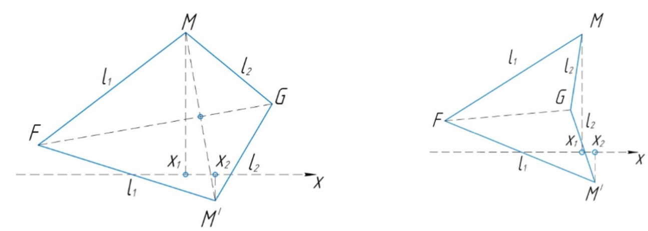


As in case a) and in case b) the points M and M^I have the same horizontal coordinate

$$x = \frac{-B}{2A},$$

(3) F lies below point G.

a)$FG > max\{l_1, l_2\}$ b)$FG < max\{l_1, l_2\}$



As you can see, the horizontal coordinate of the top point is less than the horizontal coordinate of the bottom. Therefore, if it is known that the solution should be the top point, then the horizontal coordinate of the point M is calculated by the formula:

$$x = \frac{-B - \sqrt{D}}{2A},$$

and if lower, then according to the formula:

$$x = \frac{-B + \sqrt{D}}{2A},$$

Now let us go back to the algorithm for finding the coordinates of points $M_1 - M_4$. When finding the point M_1, the role of the points F and G is played by M_0 and O_1, respectively, with $l_1 = L_1, l_2 = L_2$. Obviously, the point M_0 is on the upper semicircle, M_0 will be above the point O_1, and when on the lower - it is below the point O_1. This means that in the first case, the horizontal coordinate of the point M_1 will be located according to the formula:

$$x_1 = \frac{-B + \sqrt{D}}{2A}, \tag{18}$$

and in the second

$$x_1 = \frac{-B - \sqrt{D}}{2A}, \tag{19}$$

where the numbers A, B, C, D are found by formulas (14)–(17).

In both cases, the vertical coordinate is found by the formula

$$y_1 = \sqrt{L_2^2 - (x_1 - h_{1,x})^2} \tag{20}$$

since the point M_1, in accordance with the design, is always above the point O_1.

When finding the point M_2, the role of the points F and G is played by M_1 and O_2, respectively, with $l_1 = L_3$, $l_2 = L_4$. Therefore, the points M_1 and M_2 always lie below the point O_2, then the coordinates of the point M_2 are found by the formulas:

$$x_2 = \frac{-B + \sqrt{D}}{2A}, \quad y_2 = h_{2,y} - \sqrt{L_4^2 - (x_2 - h_{2,x})^2} \tag{21}$$

The coordinates of point M_3, as already noted, are calculated by formulas (5), (6) after the coordinates of point M_3 have been found.

When finding the point M_4, the role of the points F and G is played by M_3 and O_3, respectively, with $l_1 = L_6$, $l_2 = L_7$. Since the points M_3 and M_4, in accordance with the construction parameters, always lie below the point O_3, the coordinates of the point M_4 are found by the formulas

$$x_4 = \frac{-B + \sqrt{D}}{2A}, \quad y_4 = h_{3,y} - \sqrt{L_7^2 - (x_4 - h_{3,x})^2} \tag{22}$$

The speed of the point M_0. $V_{M0} = \omega$ $OM_0$where the angular velocity of the crank is determined by the formula

$$\omega = \frac{\pi \cdot n}{30} = \frac{3,\,14 \cdot 270}{30} = 28,\,27c^{-1}$$

M_1 point speed

$$\begin{cases} \vec{V}_{M1} = \vec{V}_{M0} + \vec{V}_{M1M0} \\ \vec{V}_{M1} = \vec{V}_{01} + \vec{V}_{M1O1} \end{cases} \tag{23}$$

M_2 point speed

$$\begin{cases} \vec{V}_{M2} = \vec{V}_{M1} + \vec{V}_{M2M1} \\ \vec{V}_{M2} = \vec{V}_{02} + \vec{V}_{M2O2} \end{cases} \tag{24}$$

The speed of the point M_3 is determined by the similarity

$$\frac{p_V m_3}{p_V m_1} = \frac{O_1 M_3}{O_1 M_1}$$

M_4 point speed

$$\begin{cases} \vec{V}_{M4} = \vec{V}_{M3} + \vec{V}_{M4M3} \\ \vec{V}_{M4} = \vec{V}_{03} + \vec{V}_{M4O3} \end{cases} \tag{25}$$

Acceleration of point M_0 at a constant angular velocity $a_{M0} = \omega^2 \cdot OM_0$

M_1 point acceleration

$$\begin{cases} \vec{a}_{M1} = \vec{a}_{M0} + \vec{a}^{\,n}_{M1M0} + \vec{a}^{\,\tau}_{M1M0} \\ \vec{a}_{M1} = \vec{a}_{01} + \vec{a}^{\,n}_{M101} + \vec{a}^{\,\tau}_{M101} \end{cases} \tag{26}$$

where the normal acceleration is a^n_{M1M0}:

$$a^n_{M1M0} = \frac{V^2_{M1M0}}{M_1 M_0} \tag{27}$$

M_2 point acceleration

$$\begin{cases} \vec{a}_{M2} = \vec{a}_{M1} + \vec{a}^{\,n}_{M2M1} + \vec{a}^{\,\tau}_{M2M1} \\ \vec{a}_{M2} = \vec{a}_{02} + \vec{a}^{\,n}_{M202} + \vec{a}^{\,\tau}_{M202} \end{cases} \tag{28}$$

where the normal acceleration is a^n_{M2M1} and a^n_{M202}:

$$a^n_{M2M1} = \frac{V^2_{M2M1}}{M_2 M_1}$$
$$a^n_{M202} = \frac{V^2_{M202}}{M_2 O_2} \tag{29}$$

The acceleration of the point M_3 is determined by the similarity

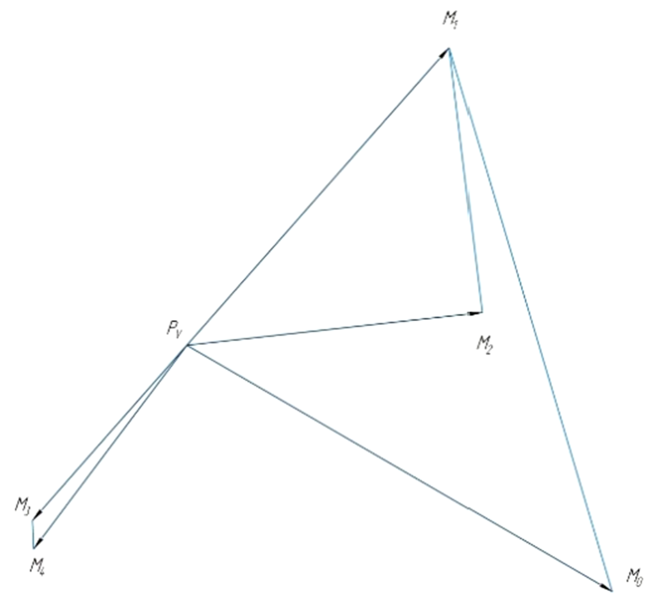


Fig. 2. The plan of the speeds of the nodal points of the CH sieve mill.

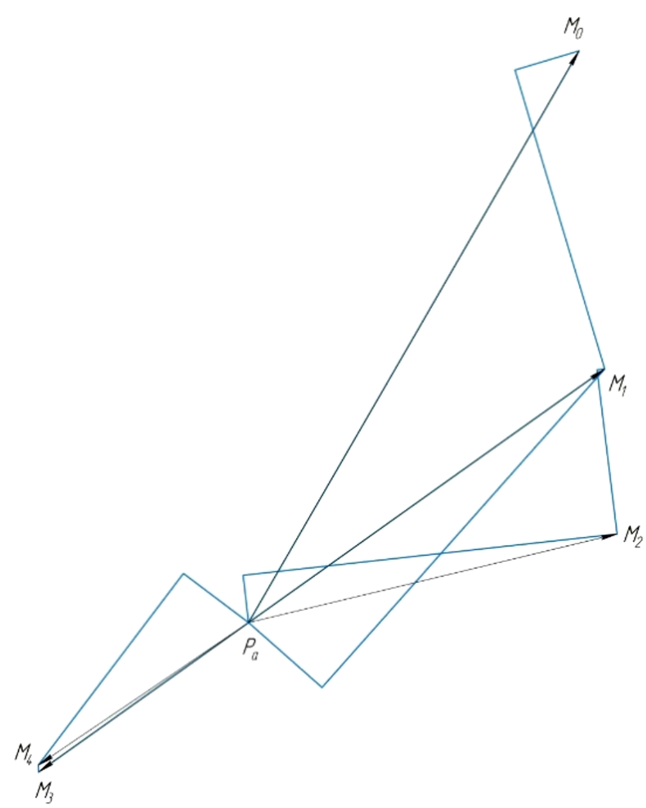


Fig. 3. The plan of acceleration of the nodal points of the CH sieve mill.

$$\frac{p_a m_3}{p_a m_1} = \frac{O_1 M_3}{O_1 M_1}$$

M_4 point acceleration

$$\begin{cases} \vec{a}_{M4} = \vec{a}_{M3} + \vec{a}^{\,n}_{M4M3} + \vec{a}^{\,\tau}_{M4M3} \\ \vec{a}_{M4} = \vec{a}_{03} + \vec{a}^{\,n}_{M403} + \vec{a}^{\,\tau}_{M403} \end{cases} \tag{30}$$

where the normal acceleration is a^n_{M4M3} and a^n_{M403}:

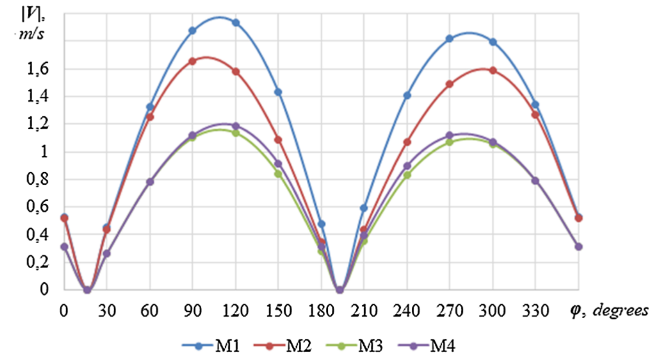


Fig. 4. Changes in the velocity modulus of the nodal points of the sieve mill from the crank position.

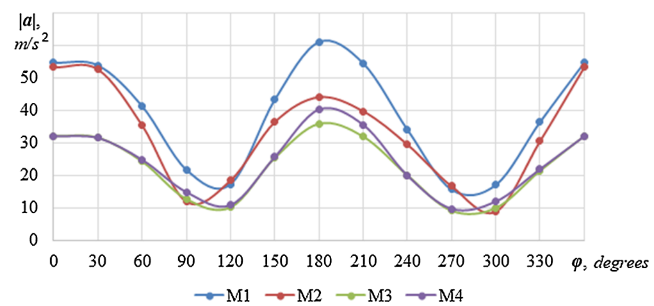


Fig. 5. Dependence of the acceleration modulus of the nodal points of the sieve mill on the crank position.

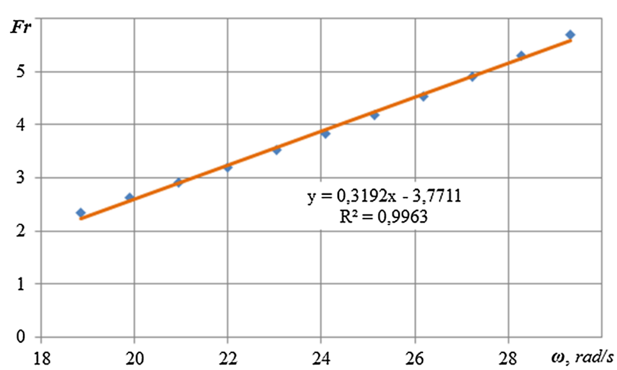


Fig. 6. The dependence of the Froude number Fr on the angular velocity of the crank.

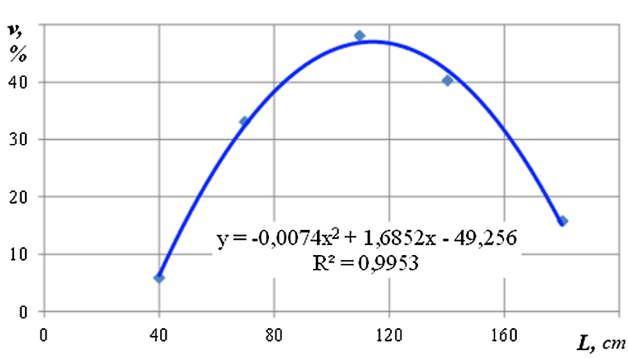


Fig. 7. Experimental results: a graph of the distribution of the coefficient of variation v of the speed of the air flow along the length L on the surface of the CH sieve.

$$a^n_{M4M3} = \frac{V^2_{M4M3}}{M_4M_3}$$
$$a^n_{M403} = \frac{V^2_{M403}}{M_4O_3} \quad (31)$$

3. Results

By a graphic-analytical method, the velocity plan and the acceleration plan for the nodal points of the sieve mill of the CH cleaning system were constructed (Figs. 2 and 3).

Since the upper sieve and the lower sieve mills operate in the opposite direction, this is indicated by the directions of the vectors of their nodal points (Figs. 2 and 3).

From the found coordinates of the possible movement of all the nodal points ($M_1 - M_4$) of the combine harvester cleaning system, it is possible to easily calculate their speeds and accelerations at any time. The changes in the velocity and acceleration modulus of the nodal points ($M_1 - M_4$) depending on the angle of rotation (position) of the crank are shown in Figs. 4 and 5.

From Figs. 4 and 5 it can be seen that the speeds and accelerations of the points of the upper sieve $M_1 - M_2$ are larger than the nodal points of the lower sieve mill $M_3 - M_4$.

The Froude number characterizes the ratio between the inertial force and the external force, in the field of which there is a movement acting on the elementary volume of gas.

Analyzing Fig. 6, we can say that an increase in the angular velocity ω of the sieve mill drive crank leads to an increase in the Froude number Fr, which according to the generally accepted classification means a turbulent flow (Fr $>$ 1). By measuring with an anemometer, the air flow rates were found above the surface of the CH upper sieve mill (see Fig. 7).

As shown by the results of measuring the air flow rate over the sieve part, it can be concluded that there is a strong divergence of air velocity along the CH cleaning system, as evidenced by the variation readings (Table 1).

To clarify the experimental data, a three-dimensional model of the existing design of the CH cleaning system was developed and implemented in the FlowVision software package (Fig. 8).

When calculating the model in the FlowVision software package, the following factors were taken into account: the centrifugal fan serves as an air flow generator and the air flow is generated by the blades by rotating the wheel (speed of 650 min^1). The program also sets the movement (oscillations) of sieves through a function according to the found coordinates of the nodal (extreme) points of the CH cleaning system (see Fig. 9).

Analyzing Fig. 10, it can be said that the air flow rates at the outlet of the blower fan channel and on the sieves of the combine harvester cleaning system are distributed unevenly. Table 2 shows a comparative analysis of statistical data measuring the speed of the air flow on the sieve of the combine harvester New Holland TX-65 and with the New Holland TX-65 installed deflectors. The deflectors are installed in the discharge channel of the fan in order to equalize the distribution of the velocity of the air flow over the entire area of the sieve.

4. Discussion

According to the variation values (Table 2), it can be said that the New Holland TX-65 combine harvester with deflectors installed has an air flow distribution across the width of the sieve mill significantly reduced from (23 … 67) to (9 … 24)%.

The experimental data of the distribution of air velocity over the entire sieve area of the existing modern CH confirmed the results of other scholars that the air flow is unevenly distributed over the sieve area and varies over a wide range (Badretdinov and Nasyrov, 2017; Miu, 2015; Spokas et al., 2016). Thus, the process of pneumatic-sieve

Table 1
Statistical analysis of the distribution of air velocity over the surface of the CH upper sieve mill (standard) along the length.

Parameter	Min.	Max.	Average value, X	Dispersion, σ^2	Average turning off, σ	Variation, ν
Velocity, m/s	3.75	10.29	6.87	3.75	1.94	28.20

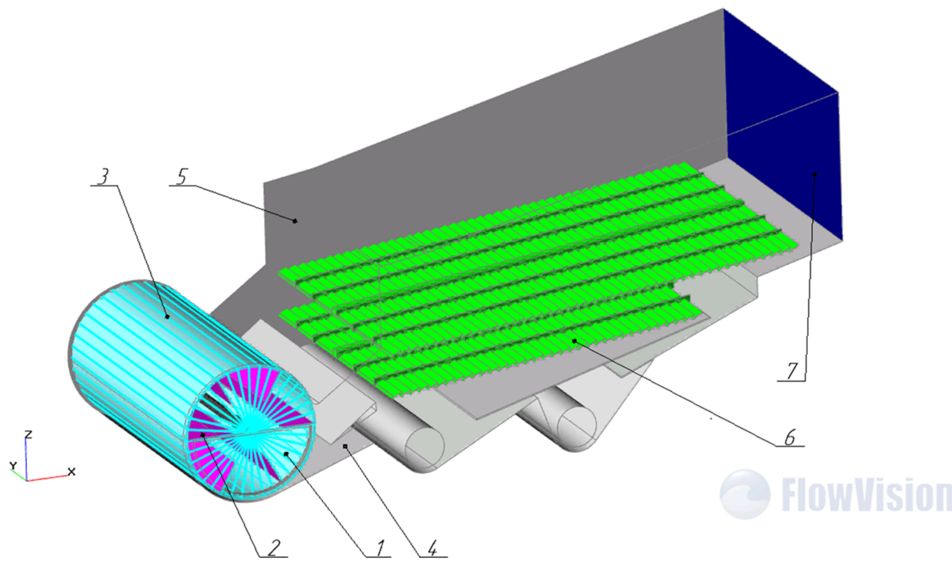


Fig. 8. Model area with boundary conditions. *Note:* 1 - airflow inlet, 2 - fan blades (rotating wall), 3 - sliding surface (movement: rotation), 4 - wall, 5 - symmetry, 6 - sieve mill (movement: oscillations), 7 - free exit.

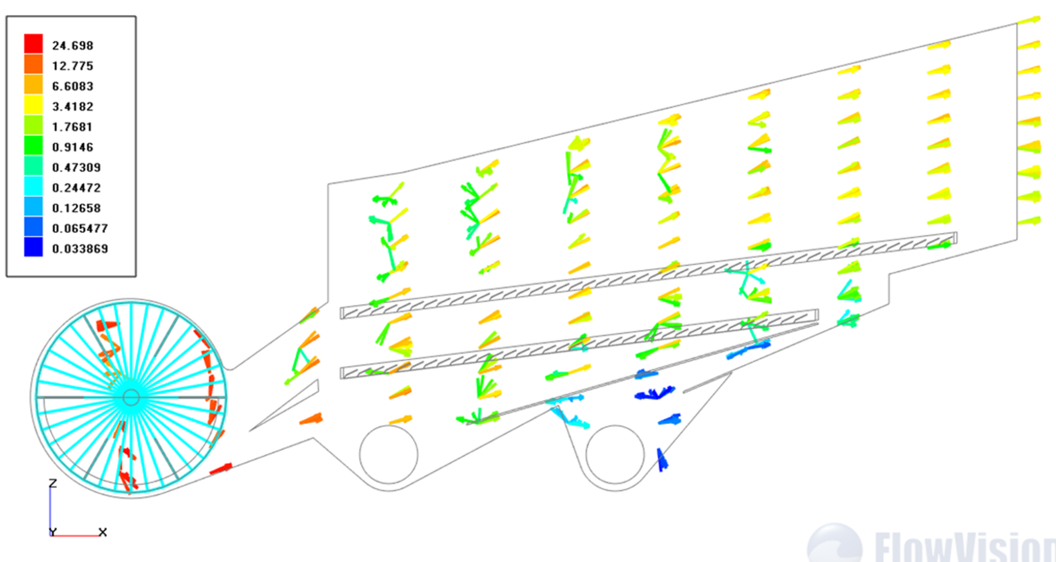


Fig. 9. The result of the calculation in FlowVision: the distribution of the velocity vectors of the air flow in the CH cleaning system.

cleaning in the CH takes place in violation of agrotechnical requirements (Steponavičius et al., 2008; Sorochenko and Mathematical, 2017; Sorochenko and Mathematical, 2016; Xu et al., 2019). Due to improved performance and throughput, problems arise in the quality of the cleaning system. This can be explained by the complexity of simultaneous regulation of several structural and technological parameters (fan speed and air flow rate U, sieve louver clearances and sieve drive crank angular velocity ω) and, depending on the crop being harvested, its physical and mechanical properties (geometric parameters, humidity, contamination). The experimental data were confirmed by theoretical studies of the mathematical description and modeling in the form of a polydisperse two-phase flow with regard to concentration, inertia, relaxation time, resistance coefficient (Alferov, 1987; Kotov and Chaus, 2010; Mirenko et al., 2011). A comparative analysis of theoretical and experimental studies has shown that reliability is greater than 0.95 by the Student's t-test, which suggests that the results can be accepted as reliable. By simulating and calculating the model of real CH using this method, problem areas of the cleaning system were identified. These problems could be solved by changing the design parameters and adding guides to the blower fan duct (patent RU 2621026 C1 and RUS 175203), which contributes to a uniform distribution of the air flow over the entire area of the CH sieve. The obtained characteristics allow us to develop recommendations for optimizing the structural and technological parameters of the fan and the cleaning system of the

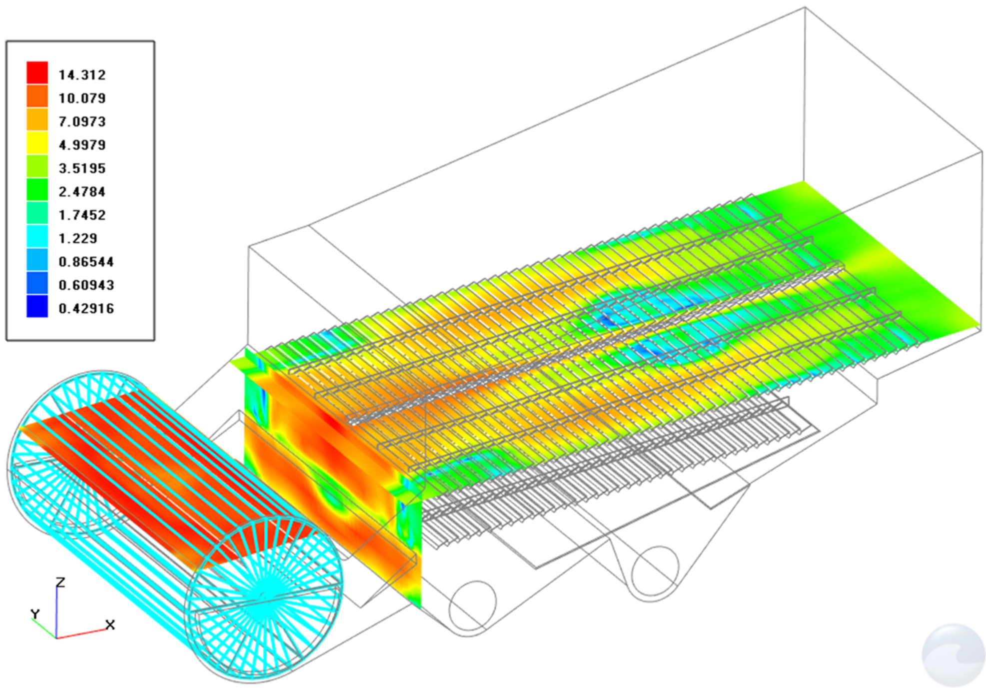


Fig. 10. The result of the calculation in FlowVision: the distribution of the air flow rate at the exit from the fan and on the CH upper sieve (pouring).

Table 2
Statistical analysis of the change in air velocity on the sieves of the combine harvester New Holland TX-65 across the sieve width.

Sieve width	1	2	3	4	5
Without deflectors					
Average value, m/s	1.19	1.41	1.23	1.47	1.20
Dispersion	0.08	0.20	0.69	0.35	0.28
Average turning off	0.28	0.45	0.83	0.59	0.53
Variation, %	23.12	31.84	67.51	40.00	44.10
With deflectors					
Average value, m/s	1.58	1.37	1.84	1.38	1.54
Dispersion	0.08	0.06	0.03	0.04	0.14
Average turning off	0.28	0.24	0.17	0.19	0.37
Variation, %	17.99	17.66	9.25	13.82	23.97

combine harvester as a whole. Using this simulation method, it is possible to improve the cleaning systems of combine harvesters without significant costs and efforts.

5. Conclusion

The coordinates of the nodal points of the sieve mill of the cleaning system of the combine harvester were determined, plans for their speeds and acceleration of motion were constructed; a mathematical model of the operation of the sieve mill of the combine harvester cleaning system has been developed; the Froude number for the sieve mill Fr = 5.3 is the ratio between the forces of inertia and gravity, in the field of which movement occurs; experimental measurements of the speed of the air flow on the surface of the sieve mill for the existing structures of the cleaning system of modern combine harvesters amounted to 3.75 … 10.2 m / s, which are implemented in the mathematical model of a complete description of the technological process of cleaning the combine harvester using methods of two-phase flow mechanics. The obtained parameters allow to establish that for modeling the technological process of the cleaning system of a combine harvester, you can use the methods of two-phase flows “gas - particles”. The obtained characteristics can serve as a basis for development of recommendations for optimizing the structural and technological parameters of the pneumatic systems of agricultural machines. Using the simulation method, it is possible to improve the pneumatic systems of agricultural machines without significant costs and efforts.

Declaration of Competing Interest

The authors declare no conflict of interest.

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