Methods for calculating basic parameters of machines for the distribution of chemical and mineral materials on highways

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Abstract. The article is devoted to determining the main parameters of the working body (an implement) of the machine for distributing chemical and mineral materials (sand) ensuring high-quality performance of works. Based on the ranking of forces acting on a sand grain located on the surface of the machine implement and eliminating forces that do not significantly affect its movement, differential equations of a particle motion are obtained. Based on the solution to the differential equation, the following parameters were obtained: the flight range of the grain, the time of movement of the grain on the disk, and the angle of its dumping. In addition, issues related to the requirements for such machines are considered. The methodology developed makes it possible to significantly reduce the time and money spent and the costs of calculating the main parameters and arrange a rational design of the machine for distributing chemical and mineral materials.

1 Introduction

In winter, various methods are used to combat road icing, for example, by using heat engines to remove ice cover from the surface. This method is frequently used when removing ice cover on roads. City management departments are equipped, in part, with vehicles for the maintenance of highways and city streets; municipal utility vehicles differ in design. For example, machines for combating ice through thermal action have engines based on the principles of turbocharging; the engines are installed on a car chassis or a special trolley. The design of the SY 3500 heat engine is of interest. This de-icing machine is designed using advanced technology. The advantages of this machine include high productivity and environmental friendliness. In addition, the machine is multifunctional, for example, it can be used as a tractor in non-winter seasons. One of the main disadvantages is the high cost of deicing work. Another common way to combat slippery roads is to spread chemical and mineral materials on the roads. This method of dealing with ice has several advantages compared to the first method; in particular, this method is characterized by low cost of work. Research is constantly being conducted to substantiate the basic design and technological parameters of a machine for distributing chemical and mineral materials.

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Zhang J., Das D.K., Peterson K. [1] conducted an analysis of the financial return in matters of seasonal maintenance of highways and city streets. The authors analyzed the costs involved in achieving effective operation of technical systems, including the wholesale price of equipment, its placement and assembly, and support. They also looked at the costs of using the equipment during the period of seasonal maintenance of highways, including operator's wages and purchase of spare parts

The German methodology to develop a model for improving the seasonal maintenance of highways deserves attention; when creating the above methodology, the main parameters were considered. In the case of developing a machine for sprinkling chemical and mineral materials, information about natural phenomena, traffic conditions, track classes, maintenance costs, etc. was used. The likelihood of the formation of road traffic incidents and their outcome, the impact on the environment of clogging from roadside debris, the use of chemical materials and the release of hazardous materials into the environment were also considered.

At present, seasonal activities in road maintenance cannot be effectively conducted without the use of municipal road equipment. Municipal road equipment is used for the mechanized cleaning of tracks from precipitation and sprinkling de-icing materials (DIM). However, municipal road vehicles consume a huge amount of fuel, generating and emitting a huge amount of harmful gases into the environment [2].

The amount of energy consumed by these road machines is related to the volume of work performed to maintain the tracks and the length of highways and city streets when clearing the tracks of sediment. The answer to solving the problem lies in improving the routes of municipal vehicles, which, in turn, makes it possible to achieve several results:

-reducing the amount of energy consumption;

-respecting environmental ecosystems and reducing wage costs;

-reducing time spent on operating processes and wage costs;

-improving the characteristics of the provided operational services;

-increasing adaptability of the population to extreme hydro-meteorological conditions.

A group of Slovenian researchers from the Institute in Maribor has created a set of documents designed to simulate rational route patterns. The package demonstrates the development of a complex system of automobile routes using the queuing method and transporter task method as an example. To apply these methods, a sequential order must be found for the communal vehicle's movement, which prohibits duplicated passes on the same path or allows only minor repetitions of the passes. The developed method was implemented at the facilities of the city municipality. The achievement of using this method is to reduce the gaps in the movement pattern by 22.7%. As a result of reducing the length of the traffic pattern, 170 liters of fuel were saved for twelve passes of municipal vehicles according to the developed schedule. In addition, a decrease in the use of chemical and mineral materials by 12.4% was recorded [3].

The only significant operational parameter of a specialized municipal machine used in emergencies is the ability to automatically separate chemical and mineral materials with control of distribution measures. As is noted in [4], when throwing chemical and mineral materials manually, it is not possible to comply with the technical conditions for combating ice (especially the concentration and uniformity of separation of materials on the surface of highways and city streets), thus, the effectiveness of seasonal measures and the positive result in de-icing processes are significantly reduced. In addition, exceeding the recommended thickness of chemicals and minerals spread on city streets has a bad effect on the environment reducing the service life of tires and road surfaces.

In [7], it was determined that significant fundamental costs associated with the use of municipal road machinery are attributed to the firms responsible for the seasonal use of such equipment. The expenses incurred by organizations with the same number of vehicles may vary considerably based on factors such as:

ownership of the communal vehicle (whether owned or leased),

duration of use,

mechanized qualities, and the need for regular maintenance and servicing.

Rational values of the main parameters of municipal and road vehicles used in the road sector were obtained in [6-9].

I. Trofimova [10] proposed to divide operational costs for municipal vehicles into one-time and actual costs. The meaning of one-time costs is that they do not depend on the amount of work and the duration of operation of the communal machine: installation, wear and tear of the machine, maintenance, etc. Production (actual) costs imply fixing of operators' income, electricity, fuel, and engine oil costs.

In [11], which differs from the above-mentioned studies, the authors obtained a formula linking the parameters of municipal equipment and the material parameters of seasonal road service. Researchers have determined that a functional connection was established between the weight indicators of a municipal machine and the intensity of the closed cycle of machine distribution. Based on this conclusion, the nonlinear effect of vehicle weight on the cost of anti-icing measures was noted. Thus, researchers aim to maximize the financial return of seasonal maintenance of highways and city streets using municipal vehicles, the weight of which is close to the rational one.

The publications of T. Khankelov et al. [12-17] highlight issues related to the development of comprehensive performance indicators for machines distributing sand and chemical reagents. In addition, it can be noted that these publications consider the issues of determining the main parameters of road vehicles; in particular, the optimal weight, productivity, energy, and material consumption of a municipal vehicle are substantiated.

Despite numerous studies, issues related to determining the optimal values of the design and technological parameters of machines for chemical and mineral materials distribution on highways remain relevant.

2 Materials and methods

As noted above, one of the main ways to combat slipperiness is to spread the road surface with sand. A view of a municipal sand distribution machine from the Mercator Company is shown in Figure 1a). Figure 1b) shows a general view of the implement of this machine with a body.

a) b)

Fig. 1. Machine for spreading sand: a) - general view of the machine; b) - the implement of the machine with a body.

Sand (a chemical reagent) is spread on the surface of automobile tracks using an implement with an axis directed upward (Figure 1 b). The implement is equipped with sides; as a result of the rotation of the implement, the material sent to the disk by the feeder is drawn into rotation, receives acceleration and, moving away from the implement, is spread in a wide strip on the upper part of the roadways behind the utility vehicle.

Sand (chemical reagents) distribution over the implement is considered a very complex process, accompanied by the impact of forces caused by several parameters. Grains of sand in contact with the implement begin to move along it until the contact with the sides. When an implement comes in contact with grains of sand, the grains start to move along the surface of the implement until they reach the sides. The way the grains move on the surface of the implement is affected by the acceleration until the grains make contact with the implement and the coordinate points where the grain touches the surface of the implement.

On the surface of the implement, sand grains move as a result of inertial and frictional forces, and the contact forces of grains with each other. The type and structure of movement is significantly influenced by inertial and frictional forces. Therefore, to simplify the solution to the problem, a grain is considered a body subject to the influence of inertial and air forces, frictional forces and forces of interaction between particles. Centrifugal and frictional forces have the most influence on the character of motion. Therefore, to simplify the solution to the problem, the particle is considered under the action of these forces only and some distorted position of the deflected edges is allowed. The diagram of the action of forces on a sand particle is shown in Figure 2.

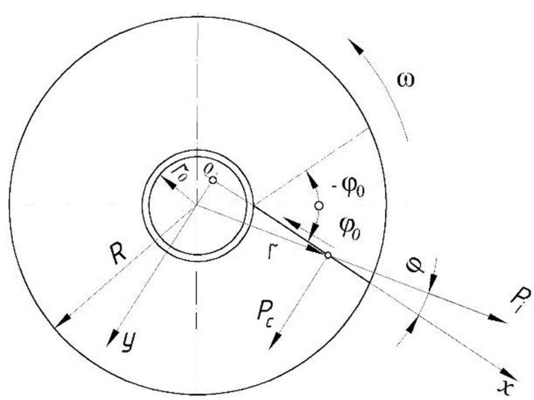

Fig. 2. Diagram of the forces acting on a sand particle.

The differential equation of motion of a particle of material along the edge of a disk located at a certain angle φ_0 to the radial position (Figure 2) has the following form:

$$m\frac{d^2x}{dt^2} = P_i cos\varphi - (P_c - P_i sin\varphi)f - Gf, \quad (1)$$

where P_i is the centrifugal force of inertia, N; P_c is the Coriolis inertia force, N; G is the weight of the particle, N; f is the coefficient of friction between the material and the steel.

These forces are:

$$P_i = m\omega^2 r; \;\; P_c = 2m\omega\frac{dx}{dt}; \quad G = mg$$

where ω is the angular velocity of the disk, 1/s.
Considering that

$$cos\varphi = \frac{x}{r} \text{ and } sin\varphi = \frac{r_0 sin\varphi_0}{r}$$

Differential equation (1) takes the following form:

$$\frac{d^2x}{dt^2} + 2\omega f \frac{dx}{dt} - \omega^2 x = \omega^2 r_0 sin\varphi_0 f - gf, \quad (2)$$

Then, the above relationship to find the distance traveled by a grain of sand in absolute motion is determined as follows:

$$x = \frac{r_0 cos\varphi_0 + k_1}{2K}\{(k+f)e^{\omega(k-f)t} + (k-f)e^{-\omega(k+f)t}\} - k_1 \quad (3)$$

To calculate the length of rebound of a grain of sand, we need to have data on the velocity of absolute movement

$$v_x = \frac{dx}{dt} = \left(\frac{r_0 cos\varphi_0 + k_1}{2K}\right)(k^2 - f^2)\omega\,\{e^{\omega(k-f)t} - e^{-\omega(k+f)t}\}, \quad (4)$$

In these formulas

$$k = \sqrt{f^2+1} \text{ and } k_1 = r_0 sin\varphi_0 f + gf\frac{1}{\omega^2}$$

The dependencies presented above were found for the implement located at the rear. If the implement is located at the front, then it is necessary to assume that $\varphi = -\varphi$ and $\varphi_0 = -\varphi_0$. Therefore, the dependencies for x and v_x will have the following form:

$$x = \frac{r_0 cos\varphi_0 + k_2}{2k}\{(k+f)e^{\omega(k-f)t} + (k-f)e^{-\omega(k+f)t}\} - k_2, \quad (5)$$

$$v_x = \frac{r_0 cos\varphi_0 + k_1}{2k}(k^2 - f^2)\omega\{e^{\omega(k-f)t} - e^{-\omega(k+f)t}\}, \quad (6)$$

In these formulas $k_2 = -r_0 f sin\varphi_0 - \frac{gf}{\omega^2}$
In the case of an axial arrangement of the implement, $\varphi_0 = 0$ and $\varphi = 0$

$$x = \frac{r_0 + k_3}{2K}\{(k+f)e^{\omega(k-f)t} + (k-f)e^{-\omega(k+f)t}\} - k_3 \quad (7)$$

$$v_x = \frac{r_0 + k_3}{2K}(k^2 - f^2)\omega\{e^{\omega(k-f)t} - e^{-\omega(k+f)t}\} \quad (8)$$

where $k_3 = -gf/\omega^2$.

The gravity force G of a grain of sand is infinitely small relative to forces of another nature, so in these cases, it is assumed that $G = 0$. Here $k_3 = 0$. Therefore, the dependences defining the sand coordinates along the *x*-axis and the velocity projection onto this axis in the case of the axial position of the implement have the following form:

$$x = \frac{r_0}{2k}\left\{(k+f)e^{\omega(k-f)t} + (k-f)e^{-\omega(k+f)t}\right\} \quad (9)$$

$$v_x = \frac{r_0}{2k}(k^2 - f^2)\omega\left\{e^{\omega(k-f)t} - e^{-\omega(k+f)t}\right\} \quad (10)$$

To justify the size of the coating and the distribution of the area relative to the edge of the technological machine, it is necessary to have data on the angle of dumping. The angle of dumping is the angle to which the implement must rotate so that a grain of sand, being at a minimum distance from the axis of rotation, can leave the surface. Therefore, in our case $x = R$.

Evaluating the dependencies developed to obtain *x,* we can conclude that the second term weakly affects the value of *x*.

For $e^{-\omega(k+f)t} = 0$, the error is no more than 1%. So, we obtain

$$R = \frac{r_0}{2k}(k+f)e^{\omega t_1(k-f)}, \quad \omega t_1 = \theta$$

where θ is the angle of dumping.

The angle of dumping in case of axial arrangement of the implement and *G*=0 is:

$$\theta = \frac{1}{k-f} ln \frac{2kR}{r_0(k+f)} \quad (11)$$

Under the same assumptions, we obtain the angle of dumping for the implement located at the rear:

$$\theta_{\text{н}} = \frac{1}{k-f} ln \frac{2k(R_1+k_1)}{r_0(k+f)(cos\varphi_0 + fsin\varphi_0)}, \quad (12)$$

and for the implement located at the front:

$$\theta_{\text{в}} = \frac{1}{k-f} ln \frac{2k(R_1-k_2)}{r_0(k+f)(cos\varphi_0 - fsin\varphi_0)}, \quad (13)$$

In formulas (12) and (13)

$$R_1 = \sqrt{R^2 - r_0^2 sin^2\varphi_0 - r_0 cos\varphi_0}$$

Analysis of these formulas shows that

$$\frac{R_1 - k_2}{cos\varphi_0 - fsin\varphi_0} > R > \frac{R_1 + k_1}{cos\varphi_0 + fsin\varphi_0}$$

Therefore, $\theta_B > \theta > \theta_{H,}$ the minimum spreading angle is possible if the implement is located on the spreading rotor at the rear. To establish the absolute velocity at which a grain of sand leaves the rotor, it is necessary to know the time interval t_1, for the grain to move along the rotor.

To simplify the calculations, Figure 3a) shows the ratio $R/r_0 = f(t)$ at different typical rotation frequencies ω and at $f = 0{,}5$ (for wet material of large dimensions). Using certain values of R, r_0, and ω, it is possible to obtain the value of t, and by substituting it into the equation expressing υ_x, to determine velocity υ_x at the time of separation of the grain of material from the rotor.

Relationship $\upsilon_x/r_0 = f(t)$, which determines the value of υ_x at certain t for several fixed values of ω, is presented in Figure 3.

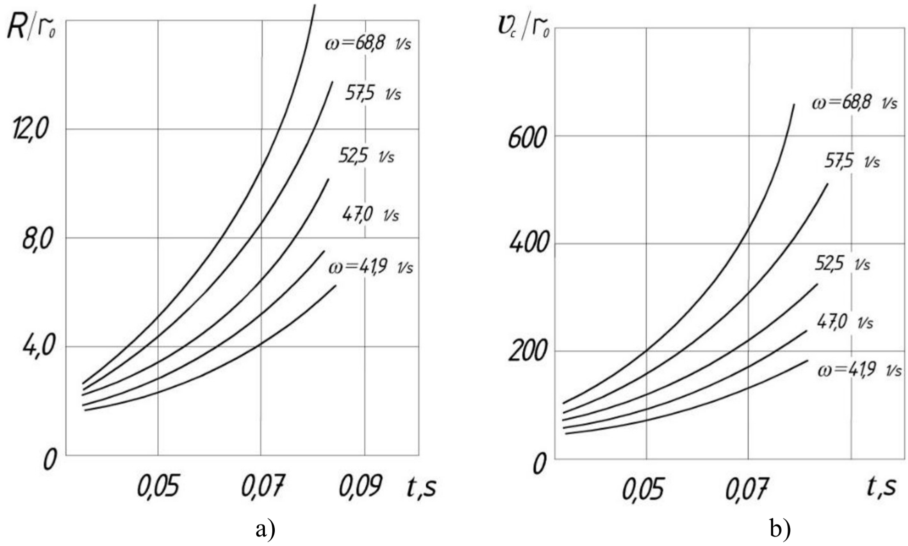

Fig. 3. The ratio of the distance covered by the implement (a) and the velocity of the grain (b) on the length.

The ratio of the distance covered by the implement and the velocity of the grain on the length of the grain along the implement is considered an absolute motion, and the circular movement of the implement is considered plane. Therefore, as the grain moves away from the implement, it acquires velocity:

$$\overline{\vartheta_a} = \overline{\vartheta_p} + \overline{\vartheta_x},$$

where ϑ_p is the circular velocity of the implement, $\vartheta_p = \omega r$.

During the spreading of sand or chemical reagents, a municipal vehicle moves at a velocity of ϑ_m. Consequently, the grain separated from the implement has a velocity of $\bar{\vartheta} = \overline{\vartheta_a} + \overline{\vartheta_m}$ relative to the road. When separated from the implement, the grain moves in space. During the period of grain motion in space, the forces of gravity and air resistance affect it. Examining the probable limits of variation in the Reynolds number *Rₑ* and using the results of the empirical substantiation of the coefficient of resistance to the movement of a grain of sand in space, it is necessary to conclude that for a given type of movement, parameter *C* does not depend on the value of R_e. The calculation scheme for determining the law of grain motion in space is shown in Figure 4.

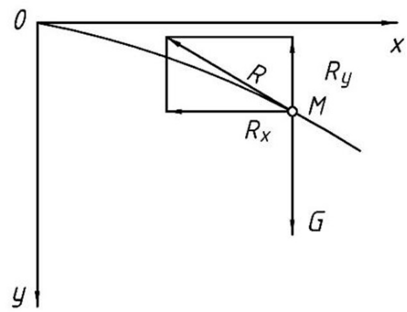

Fig. 4. Diagram of the forces acting on a sand grain when it moves in the air.

Differential equations of motion of a particle in the air (Figure 4) have the following form:

$$m\frac{d^2x}{dt^2} = -R_x, \tag{14}$$

$$m\frac{d^2y}{dt^2} = -R_y, \tag{15}$$

where R_x and R_y are the projections of the air resistance force onto the *x*- and *y*-axes.

Simplifying the problem to obtain the final solution, we accept that the values of R_x and R_y are determined by the projections of the motion velocity onto the coordinate axes, rather than its magnitude.

Then R_x and R_y can be expressed as:

$$R_x = C\frac{\rho\vartheta_x^2}{2}F \text{ and } R_x = C\frac{\rho\vartheta_y^2}{2}F, \tag{16}$$

where ρ is the air density; *F* is the area of projection of the grain onto a plane normal to the direction of motion; ϑ_x and ϑ_y are the projections of motion velocity on coordinate axes.

Then the differential equations have the following form:

$$\frac{d\vartheta_x}{dt} = -k_3\vartheta_x^2, \quad \frac{d\vartheta_y}{dt} = g - k_3\vartheta_y^2, \tag{17}$$

where $k_3 = \frac{C\rho F}{2m}$.

The solution to these differential equations is:

$$x = \frac{1}{k_3} ln k_3\vartheta\left(t + \frac{1}{k_3\vartheta}\right), \tag{18}$$

$$y = \frac{1}{k_3} ln\frac{e^{t\sqrt{gk_3}} + e^{-t\sqrt{gk_3}}}{2}, \tag{19}$$

$$t = \frac{1}{2\sqrt{gk_3}} ln\frac{\sqrt{\frac{g}{k_3}} + \vartheta_y}{\sqrt{\frac{g}{k_3}} - \vartheta_y} + \frac{1}{k_3\vartheta}, \tag{20}$$

where ϑ is the initial velocity of the particle.

To determine the length of rebound, i.e., the values of x, is possible by calculating the rebound period t.

The value of t can be justified by applying dependence (19), taking y to be equivalent to the installation height of the implement above the horizon H.

Figure 5 shows dependence $H = f(t)$, obtained by solving the equation that expresses y.

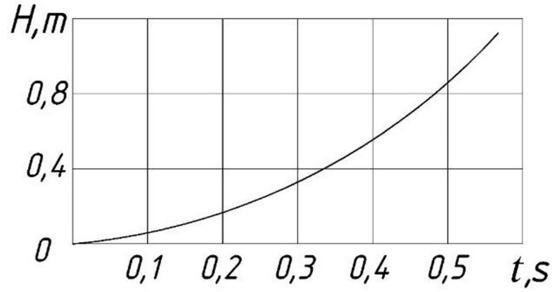

Fig. 5. Dependence of the lowering length of a sand particle on time.

When solving this equation based on experimental data, the following was accepted:

$$C = 0{,}4;\ d_{av} = 0{,}002\ m.$$

Nowadays the volumes of work related to sprinkling of chemical reagents outstrip the volumes of work related to spreading motorways with sand, so the tasks of uniform sprinkling of materials along the dimensions of the road become relevant. When using chemical reagents, the sizes of the grains fluctuate within a narrow range; therefore, as experiments show, when the grains meet the implement, the material falls at equal distances from the centre of the disc.

For this option, it is possible to assume that a strip where the grains meet the road surface is in the form of a ring. Consequently, the sprinkling of chemical reagents along the contour of the processed strip will be uneven, and the unevenness will increase beginning from the axis of the machine to the boundaries of the processed strip (Figure 6).

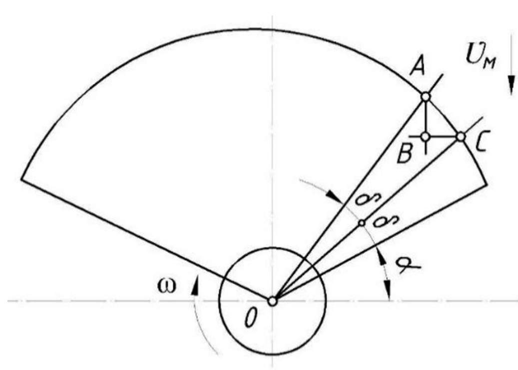

Fig. 6. Scheme of spreading sand.

The uniformity coefficient of material distribution can be either

$$K_{un} = \frac{AC}{BC} \quad \text{or} \quad K_{un} = \frac{1}{\sin(\alpha + n\delta)}$$

At the boundary of the processed strip, it is $K_{un} = \frac{1}{\sin\alpha}$.

The experience of operation of municipal machines shows that unacceptable improbability can be expressed by a uniformity coefficient equal to $K_{un} = 1.25$. Such a coefficient can be ensured with the accepted pattern of distribution if the angle is $\alpha = 53^0$. Consequently, the particles of material must be dumped in an arc with an angle of 74°.

3 Results and discussion

In the case of designing a municipal machine, it is necessary to solve two problems that justify the values of the indicators and the technological mode of operation of the sprinkling implement: ensuring the required overall dimensions of the strip and guaranteeing the necessary uniformity of the sprinkling thickness, and stating the strip relative to the axis of the municipal machine. The answer to this question must be sought by solving the problem of determining the rational location of the disk of the machine implement and the coordinates of the material supply to the disk. In this option, if a chemical reagent or sand comes into contact at high velocities, then upon impact the grains will rebound and fall out at short distances from the disk.

To avoid this process, grains of sand must be met on those rings of the disk where the rotational velocity is less than 8 m/s. Therefore, the area where sand is supplied to the disk should be at a distance from the axis of rotation of no more than

$$r' = \frac{8}{\omega}.$$

In addition, to move particles to the periphery, they must arrive at the disk no closer than the distance from its center,

$$r'' = (1{,}1 \ldots 1{,}2) r_0.$$

The provided ratios allow us to identify the area where the material supply point should be placed, as shown in Figure 7. When selecting the position of the window and its shape through which the material is fed into the disk, we can initially consider the following factors.

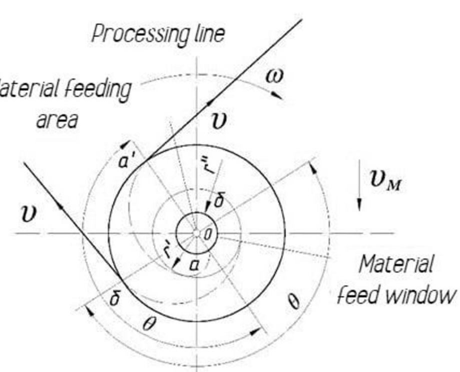

Fig. 7. Scheme of sand feeding to the disk.

Using the formula for determining the angle of dumping, for example, under the radial position of edges, we obtain:

$$\theta = \frac{1}{k-f} ln \frac{2kR}{r_0(k+f)}, \quad (21)$$

where $r_0 -$ is the distance from the axis of rotation of the disk to the point at which grains of sand fall onto the disk. Based on these data, it is possible to calculate the angle of rotation of the disk required for the rebound of grains of sand from the zone of material feeding to the disk to the periphery. The extreme positions of the point where particles come off the disk must be at an angle accepted based on the given indicators of uniformity of material distribution. By knowing the direction of the material particle escape at the boundaries of the sector, it is possible to determine the flight range of the particles and, consequently, the width of the strip processed by machine, using the above formulas and the accepted height of the disk above the road surface.

It should be borne in mind that the position of the point where the material is fed to the disk determined in this way is approximate and must be clarified when setting up the prototype.

4 Conclusions

1. By solving differential equation (2), dependencies (3) and (4) were obtained, enabling the calculation of the length of rebound and the velocity of sand particles.

2. The angle of dumping (11) and other similar dependencies, such as (12) and (13), were analyzed for various positions of the disk edge. This helped in developing condition $\theta_B > \theta > \theta_{H,}$ that ensured a uniform thickness of sand spreading.

3. To quantify the distribution of material across the width of the processed strip, a uniformity coefficient was introduced. The limiting value of the uniformity coefficient was determined to be $K_{un} = 1.25$ and conditions for ensuring this value of the coefficient were set.

4. The maximum rotational velocity of the disk was determined to be $\vartheta_d = 8$ m /s, at which the rebound of sand particles resulting from collision with the disk surface was avoided.

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