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**Serhii Pylypaka[1*], Mykola Klendii[2]**

[1]National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony, Kyiv, Ukraine

[2]Separated Subdivision of National University of Life
and Environmental Sciences of Ukraine "Berezhany Agrotechnical Institute"
47501, 20 Academichna Str., Berezhany, Ternopil region, Ukraine

# Transportation of a Material Particle by the Operating Mechanism of an Agricultural Machine in the form of a Vertical Screw Confined by a Coaxial Stationary Cylinder

**Abstract.** The use of vertical augers in screw conveyors significantly expands the operational capabilities of such mechanisation equipment for performing loading and unloading technological operations. However, the existing designs of vertical screws do not fully meet the operational requirements. Their main disadvantages are increased energy consumption, especially with their significant overall dimensions, which depend on the influence of friction of the process material on the conveyor surfaces. Therefore, the study considers the movement of a material particle by the operating mechanism of an agricultural machine in the form of a vertical screw confined by a coaxial stationary cylinder and establishes the dependence of the speed of transportation of a material particle on the influence of the particle friction coefficient on the surface of the screw and on the surface of the limiting cylinder. The purpose of the study is to determine the parameters of the movement of agricultural material particles when they interact with the helical surface of the operating mechanism of a vertical conveyor in the form of a screw that rotates around the axis and the surface of a coaxial fixed cylindrical casing. Mathematical modelling of the processes of movement of soil particles along the helical surface of the operating mechanism is described on the basis of general laws and principles of analytical and differential mathematics, theoretical and analytical mechanics. As a result of the study, the differential equations of movement of a particle of agricultural material on the helical surface of the screw, which rotates around its axis in a fixed cylinder, were compiled. The equation is solved using numerical methods and the trajectories of the relative motion of the particle along the helical line – the edge of the screw, which is common to the surface of the screw and the limiting cylinder are constructed. The friction forces of the material particle on the surfaces of the screw and casing are also considered. The limit value of the helical line lifting angle is found when the particle lifting becomes impossible at a given angular velocity of screw rotation. The influence of the friction angles and radius of the limiting cylinder on the particle lifting speed is estimated. Graphs of kinematic characteristics as a function of time are given. The materials of the study can be used by researchers for further investigation and by practitioners in the selection of conveyors for transporting agricultural materials

**Keywords**: conveyor, helical surface, angular and linear velocities, limiting casing, differential equations of motion, kinematic parameters

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## INTRODUCTION

The helical surface in the form of a screw is a structural element of many transport and technological agricultural machines, which is widely used in screw conveyors for transporting technological agricultural material. Forces act between the particles of the material, but they can be ignored or neglected when the body is small in size, taking it as a material point [1] or in the case of moving the particle at a low speed, which occurs in lifting and transport machines [2]. It is also important to investigate the movement of material particles along helical surfaces that rotate around their axis. In [3], the movement of particles

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*Corresponding author

by a vertical screw from the axis of rotation to the meeting with a cylindrical casing is studied. The particles move up after they meet the bounding cylinder. The paper investigates the movement of a particle of agricultural material, which interacts with two surfaces: the movable helical surface of the screw and the fixed surface of the cylinder.

The nature of material particles is quite broad. They can be not only mechanical particles, but also gas or liquid particles that interact with moving surfaces [4]. The movement of mechanical particles on the surface of a mobile tillage spherical disk is considered in [5], on the surface of a cylinder – in [6], on the surface of a cone – in [7]. Consideration of the movement of particles on helical surfaces is of practical importance, since such surfaces are used in screw conveyors [8; 9] and separators [10]. The use of a helical surface for calculating and manufacturing helical working elements is considered in [11; 12]. The theory of designing and constructing linear surfaces is highlighted in [13]. In [14], the practical possibility of using a screw operating mechanism for tillage is substantiated.

But today, the process of transporting a material particle by the operating mechanism of an agricultural machine remains rather neglected, in particular, the investigation of the interaction of material particles with a helical operating mechanism, the working surface of which is made in the form of a screw and a coaxial stationary cylinder, which are considered in the paper.

*The purpose of the study* is to theoretically investigate the movement of particles of agricultural materials when they interact with the helical surfaces of the operating mechanism of a vertical conveyor in the form of a screw and the surfaces of a stationary cylinder.

## MATERIALS AND METHODS

Mathematical modelling of the movement of particles of agricultural materials is described based on general laws and principles of analytical and differential mathematics, theoretical and analytical mechanics, surface theory, and computer graphics systems. The results of the conducted theoretical studies are analysed using methods of numerical integration of differential equations to find primitive functions, using the *Simulink* package of the *MatLab* system.

In [3], it is shown that when a particle moves under its own weight along a helical surface, it moves away from its axis. This is conditioned by the fact that the particle moves along a curved trajectory, resulting in a centrifugal force that causes the particle to move to the periphery. If the screw rotates around the axis, then the particle of agricultural material performs a complex movement: sliding on the helical surface and rotating around the axis of the screw, which also causes it to move towards the cylindrical casing. The material particle slides along the helical surface, simultaneously contacting the surface of the screw and cylinder. Parametric equations of a helical line have the form:

$$x = R\cos\alpha;\ y = R\sin\alpha;\ z = R\alpha\,\mathrm{tg}\beta; \tag{1}$$

where $R$ – cylinder radius – constant value; $\beta$ – screw helical line lifting angle –constant value; $\alpha$ – angle of rotation of a point on a helical surface – independent variable.

The helical line (1) passes through two surfaces: the screw and the cylinder. When a particle comes into contact with these surfaces, reaction forces occur that are directed along the normal to them.

The helical surface is formed by rectilinear generatrix that are parallel to the horizontal plane, and one end of these generatrix runs along the helical line (1), and the other is directed to the axis of the helical surface (Fig. 1a). The parametric equations of the screw have the form:

$$\begin{aligned} X &= (R-u)\cos\alpha; \\ Y &= (R-u)\sin\alpha; \\ Z &= RR\alpha\,\mathrm{tg}\beta \end{aligned} \tag{2}$$

where $u$ – value of a rectilinear helical forming surface – the second independent surface variable.

When the value of the value $u=R-r$, where $r$ – radius of the screw shaft, the surface is confined by two helical lines (Fig. 1a). When $u=0$, the parametric equations of the screw helical line are obtained (1). To make the helical surface equations different from the helical line equations, they are denoted by lowercase letters for the line and uppercase letters for the surface.

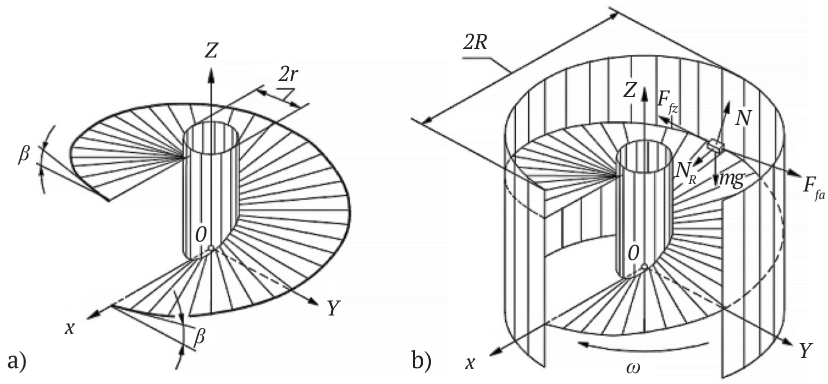


**Figure 1.** Scheme of transportation of a material particle by the screw:
a) turn of the helical surface of the screw, b) diagram of the forces applied to the particle

When rotating at angular velocity $\omega$, a material particle located on the helical line (1) simultaneously contacts the movable helical surface and the fixed surface of the cylinder (Fig. 1b). The following forces are applied to the material particle: reaction $N$ of screw surface, weight force, reaction $N_R$ of cylinder, and friction force $F_f$ (Fig. 1b). If the particle rises up in absolute motion, then the friction force on the helical surface $F_{fa}$ is sent in the opposite direction of its sliding, and on the surface of the casing $F_{fc}$ – in the opposite direction of movement (Fig. 1b).

The equation of motion of a material particle in the form $m\overline{a}=\overline{F}$ is created, and this equation is written in projections on the axis of the spatial coordinate system $OXYZ$.

The helical surface rotates around an axis at a certain angular velocity $\omega$ and over time $t$ it will return at an angle that is equal to $\alpha_a=-\omega t$ and will move in a helical line along a certain trajectory according to equations (1). The direction of rotation of the helical surface must be chosen so that the material particle can rise up in absolute motion. The helical line of the screw (1) is moved around the axis $OZ$ on the corner $\alpha_a=-\omega t$:

$$\begin{gathered} x_a=R\cos\alpha\cos(-\omega t)-R\sin\alpha\sin(-\omega t)=R\cos(\omega t-\alpha);\\ y_a=R\cos\alpha\sin(-\omega t)-R\sin\alpha\cos(-\omega t)=R\sin(\omega t-\alpha);\\ z_a=R\alpha\,\mathrm{tg}\beta. \end{gathered} \tag{3}$$

The obtained equations (3) consider rotation by angle $\alpha=\alpha(t)$ in the relative motion of the material particle and at an angle $\alpha_a=-\omega t$ in figurative motion, therefore, they are equations of absolute motion.

Projections of the absolute velocity vector are obtained by differentiating equation (3) over time $t$:

$$\begin{gathered} x'_a=-R(\omega-\alpha')\sin(\omega-t\alpha);\\ y'_a=-R(\omega-\alpha')\cos(\omega-t\alpha);\\ z_a=R\alpha'\mathrm{tg}\beta. \end{gathered} \tag{4}$$

The speed value is (4):

$$\begin{aligned} V_a&=\sqrt{x_a'^2+y_a'^2+z_a'^2}=\\ &=\frac{R}{\cos\beta}\sqrt{\omega(\omega-2\alpha')\cos^2\beta+\alpha'^2} \end{aligned} \tag{5}$$

The projection of a unit vector that sets the direction of the absolute velocity of a material particle is equal to:

$$\begin{aligned} T_{Vax}&=-\frac{(\omega-\alpha')\sin(\omega t-\alpha)\cos\beta}{A};\\ T_{Vay}&=-\frac{(\omega-\alpha')\cos(\omega t-\alpha)\cos\beta}{A};\\ T_{Vaz}&=\frac{\alpha'\sin\beta}{A}, \end{aligned} \tag{6}$$

where $A=\sqrt{\omega(\omega-2\alpha')\cos^2\beta+\alpha'^2}$.

Absolute acceleration $w$ of particle is obtained by differentiating equation (4):

$$\begin{gathered} x''_a=R''\alpha\sin(\omega t-\alpha)-R(\omega-\alpha')^2=\cos(\omega t-\alpha);\\ y''_a=R''\alpha\cos(\omega t-\alpha)+R(\omega-\alpha')^2=\sin(\omega t-\alpha);\\ z''_a=R\alpha''\mathrm{tg}\beta. \end{gathered} \tag{7}$$

Projections of the friction force vector $F_{fa}$ are found by differentiating equations (1):

$$\begin{gathered} x'=-R\alpha'\sin\alpha;\\ y'=-R\alpha'\cos\alpha;\\ z'=R\alpha'\mathrm{tg}\beta. \end{gathered} \tag{8}$$

The relative velocity of a material particle is equal to:

$$V=\sqrt{x'^2+y'^2+z'^2}=\frac{R\alpha'}{\cos\beta}. \tag{9}$$

The value of the projections of the unit vector of relative velocity is obtained by dividing the projections of this velocity by its absolute value:

$$T_{Vx}=-\cos\beta\sin\alpha;\ T_{Vy}=-\cos\beta\cos\alpha;\ T_{Vz}=-\sin\beta. \tag{10}$$

For the force $F_{fa}$ to be applied at the point where the material particle is located, the projections of the unit vector of relative velocity should be rotated by the value $(-\omega t)$ around the axis $Oz$:

$$\{\cos\beta\sin(\omega t-\alpha);\ \cos\beta\cos(\omega t-\alpha);\ \sin\beta\}. \tag{11}$$

The vector of the normal to the helical surface is defined as the partial derivative of the screw equations (2) :

$$\begin{aligned} \frac{\partial X}{\partial\alpha}&=-(R-u)\sin\alpha; & \frac{\partial X}{\partial u}&=-\cos\alpha;\\ \frac{\partial Y}{\partial\alpha}&=(R-u)\cos\alpha; & \frac{\partial Y}{\partial u}&=-\sin\alpha; \end{aligned} \tag{12}$$

The vector product of the obtained vectors is defined (12):

$$\begin{gathered} \begin{vmatrix} X & Y & Z\\ -(R-u)\sin\alpha & (R-u)\cos\alpha & R\,\mathrm{tg}\beta\\ -\cos\alpha & -\sin\alpha & 0 \end{vmatrix}=\\ =\{R\,\mathrm{tg}\beta\sin\alpha;\quad R\,\mathrm{tg}\beta\cos\alpha;\quad R-u\} \end{gathered} \tag{13}$$

Vector (13) is not singular and its place on the surface is determined by coordinates: $u$ and $\alpha$. To find the normal to the screw surface, the vector (13) is substituted in the expression $u$=0 and its expression is reduced to a single one:

$$\{\sin\beta\sin\alpha;\ -\sin\beta\cos\alpha;\ \cos\beta\}. \tag{14}$$

The normal to the cylindrical casing is also found:

$$\{-\cos\alpha;\ -\sin\alpha;\ 0\}. \tag{15}$$

For the above reasons, the unit vectors (14), (15) are rotated by the angle $(-\omega t)$ and the expression of the unit vector of the normal to the helical surface at the particle placement point is written as:

$$\{\sin\beta\sin(\omega t\text{-}\alpha); -\sin\beta\cos(\omega t\text{-}\alpha); \cos\beta\}. \qquad (16)$$

The value of the unit vector of the normal to the cylindrical casing at the particle location takes the form:

$$\{-\cos(\omega t\text{-}\alpha); \sin(\omega t\text{-}\alpha); 0\}. \qquad (17)$$

Unit vector of particle weight force $mg$, which is directed downwards, is defined by projections:

$$\{0; 0; -1\}. \qquad (18)$$

The value of the friction forces $F_{fa}$ and $F_{fc}$ can be determined by the reaction values of the surface and the corresponding coefficient of friction: $F_{fa}=f_N$, $F_{fc}=f_R N_R$, where $f$ and $f_R$ – coefficients of friction of the material particle on the helical surface of the screw and the cylindrical casing, respectively.

Making up the equation of motion $m\overline{a}=\overline{F}$ , it is written in projections on the axis of the spatial system, considering the directions (6), (11), (16), (17), and (18) of relevant forces $F_{fc}=f_R N_R$, $F_{fa}=f_N$, $N$, $N_R$ and weight forces $mg$:

$$mx''_a = f_R N_R \frac{(\omega-\alpha')\sin(\omega t-\alpha)\cos\beta}{\sqrt{\omega(\omega-2\alpha')\cos^2\beta+\alpha'^2}} - fN\cos\beta\sin(\omega t-\alpha) - N\sin\beta\sin(\omega t-\alpha) - N_R\cos(\omega t-\alpha);$$

$$my''_a = f_R N_R \frac{(\omega-\alpha')\cos(\omega t-\alpha)\cos\beta}{\sqrt{\omega(\omega-2\alpha')\cos^2\beta+\alpha'^2}} - fN\cos\beta\cos(\omega t-\alpha) - N\sin\beta\cos(\omega t-\alpha) + N_R\sin(\omega t-\alpha);$$

$$mz''_a = -f_R N_R \frac{\alpha'\sin\beta}{\sqrt{\omega(\omega-2\alpha')\cos^2\beta+\alpha'^2}} - fN\sin\beta + N\cos\beta - mg. \qquad (19)$$

To obtain a system of equations with functions: $\alpha=\alpha(t)$, $N=N(t)$ and $N_R=N_R(t)$, the expressions for absolute acceleration from equation (7) are substituted in (19), and $\alpha''$, $N$, $N_R$ is defined:

$$\alpha'' = f_R(\omega-\alpha')^2\cos\beta\frac{\omega\cos\beta(\cos\beta-f\sin\beta)-\alpha'}{\sqrt{\omega(\omega-2\alpha')\cos^2\beta+\alpha'^2}} - \frac{g\cos\beta}{R}(f\cos\beta+\sin\beta). \qquad (20)$$

$$N = m\cos\beta\left(g+\frac{f_R R\omega(\omega-\alpha')^2\sin\beta}{\sqrt{\omega(\omega-2\alpha')\cos^2\beta+\alpha'^2}}\right). \qquad (21)$$

$$N_R = mR(\omega-\alpha') \qquad (22)$$

To obtain solutions to differential equations, it is necessary to use numerical methods.

## RESULTS AND DISCUSSION

The composite equations of motion of a material particle can only be solved by numerical methods. When $\beta=10^0$, $R$=0.1 m, $\omega=15\ s^{-1}$, $f=f_R=0.3$, obtain $\alpha'=2.1\ s^{-1}$. When $\beta=20^0$ and unchanged other parameters, obtain: $\alpha'=-0.5\ s^{-1}$. It is also obtained that when $\beta=10^0$ the particle is moving up (Fig. 2a), and when $\beta=20^0$ – on the contrary-down (Fig. 2b). When $\alpha'=0$ the particle "sticks" and rotates in absolute motion in a circle. Therefore, the corresponding angle $\beta$ of lifting the auger line of the screw is found by equation:

$$\beta = \mathrm{Arctg}\frac{Rf_R\omega^2 - fg}{Rf_R f\omega^2 + g}. \qquad (23)$$

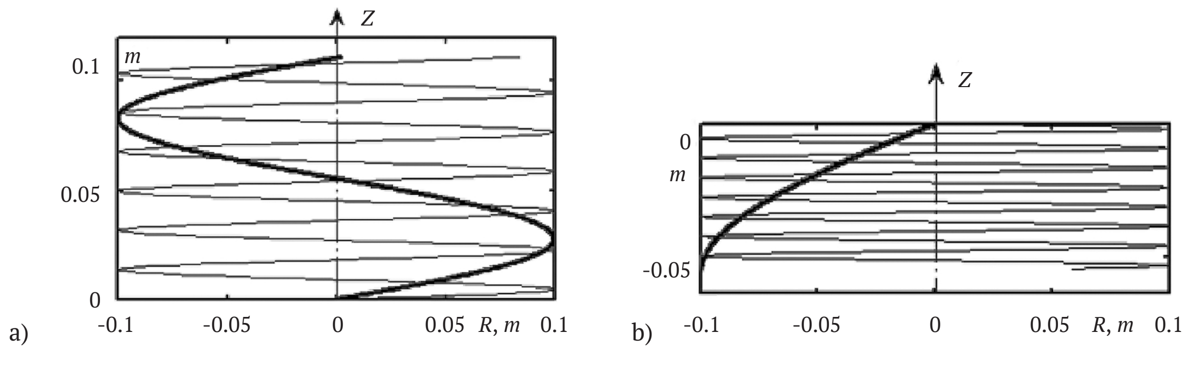


**Figure 2.** Trajectories of movement of a material particle at $R$=0.1 $m$, $\omega=15\ s^{-1}$, $f=f_R=0.3$
a) when $\beta=10^0$ – upward movement of the particle; b) when $\beta=20^0$ – downward movement of the particle

According to (23) for $R$=0.1 $m$, $\omega=15\ s^{-1}$ and $f=f_R$=0,3 the limit value of the helical line lifting angle is $\beta=17.8^0$. If $\beta\geq17.8^0$, then the rise of the particle at the specified parameters becomes impossible. As the angular velocity of rotation of the helical surface increases, the limit value of the angle $\beta$ also grows, but up to a certain limit. Next, the study finds the limit to which equation (23) approaches with an unlimited increase in the angular velocity of rotation $\omega$:

$$\lim_{\omega\to\infty}\mathrm{Arctg}\frac{Rf_R\omega^2 - fg}{Rf_R f\omega^2 + g} = \mathrm{Arcctg}\, f. \qquad (24)$$

Arctg $f$ is the angle of friction of the particle on the surface of the screw and in this case, Arctg 0.3 =16.7$^0$. Lifting angle limit value $\beta$ according to (24) is Arcctg 0.3=73.3$^0$, that is, these two angles add up to a right angle. When $\beta \geq 73.3^0$ lifting the particle up is not possible at any angular speeds of rotation of the helical surface.

If a specific angular velocity $\omega$ of screw rotation is set, then the limit value of the helical line lifting angle can be found by equation (23). At this interval (from zero to the limit value), there is a specific angle $\beta$, which provides the highest speed of particle transport up. The problem is reduced to finding the maximum value of the last expression in equations (4) or (8), since the vertical components of the relative and absolute velocities are equal.

Since equation (20) for a stationary process at $\alpha''=0$ is necessary to solve by numerical methods to find the value of the angular velocity $\alpha'$ sliding of the particle, then finding the optimal angle $\beta$ will be implemented in two stages. At the first stage, the value $\alpha'$ is found from equation (20) for the specified angles $\beta$ from the acceptable range of their values. At the second stage, substituting the obtained values $\alpha'$ and corresponding angles $\beta$ in the last expression in equations (4) or (8), the vertical component of the particle velocity is obtained. This data can be used to plot the dependency $z'=z'(\beta)$, from which the optimal angle value $\beta$ is determined. The study provides a simplified version of the calculation for $\omega$=15 $s^{-1}$ (acceptable range of values of angle $\beta$=0…17.8$^0$):

$\beta$=50; $\alpha'$=3.53 $s^{-1}$; $z'$=0.03 m/s;
$\beta$=100; $\alpha'$=2.08 $s^{-1}$; $z'$=0.037 m/s;
$\beta$=150; $\alpha'$=0.73 $s^{-1}$; $z'$=0.02 m/s.

From the results obtained, it can be seen that the highest rate of particle transport up is provided by the angle $\beta$=10$^0$. Using the same calculation method, the optimal angle value $\beta$ is found at the value of the angular velocity $\omega$=25 $s^{-1}$: $\beta$=20$^0$. In this case, the vertical component of the particle velocity is $z'$=0.29 m/s. Considering that the permissible interval of angle values for speed $\omega$=25 $s^{-1}$ makes up $\beta$=0…45.7$^0$, then it can be concluded that the optimal value of the angle $\beta$ is close to the average value of the allowed interval. In [8], an equation for determining this angle is given for the case when the angular velocity of rotation of the screw increases indefinitely ($\omega \to \infty$):

$$\beta = 45^0 - 0.5\text{Arctg}f \qquad (25)$$

From (25) for $f$=0.3 obtain: $\beta$=36.65$^0$. This value is exactly two times less than the limit value ($\beta$=73.3$^0$), that is, it is exactly in the middle of the allowed interval.

Next, the study considers how the coefficients of friction f and fR affect the speed of lifting the particle. When the coefficient of friction $f$ decreases, angular velocity $\alpha'$ of sliding of a material particle increases, and its maximum value is reached at the value of $f$=0, that is, for a completely smooth helical surface. Fig. 3a shows the graphical relationship $\alpha'=\alpha'(f)$ when $R$=0.1 $m$, $\omega$=25 $s^{-1}$, $f_R$=0.3, $\beta$=20$^0$.

Reduction of the coefficient of friction $f_R$ of the particle along the cylinder leads to a decrease in the angular velocity $\alpha'$ of movements of a material particle (Fig. 3b). Reduction of $f_R$ leads to lowering of the material particle. The limit is the value of $f_R$ when $\alpha'$=0. By solving (23) with respect to $f_R$, the following is obtained:

$$f_R = \frac{g(f + \text{tg}\beta)}{R\omega^2(1 - f\,\text{tg}\beta)}. \qquad (26)$$

For the given data from (26), the limit value of the friction coefficient $f_R$: $f_R$=0.12 is found.

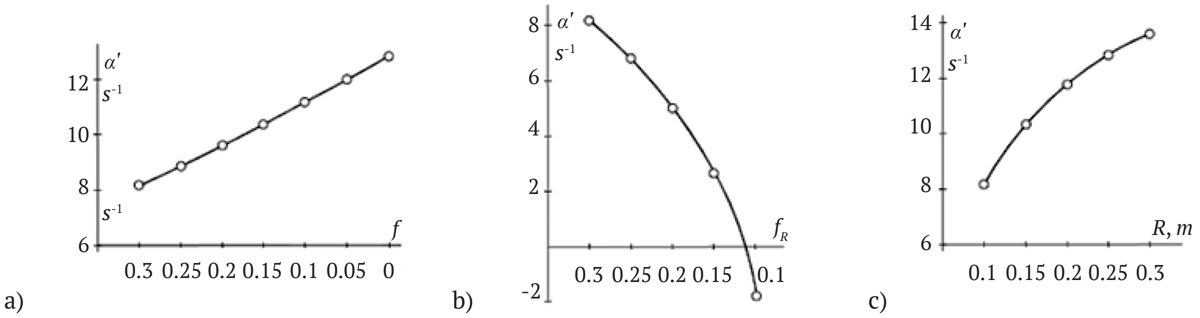


**Figure 3.** Graphical dependences of the angular velocity of a particle $\alpha'$ when $\omega$=25 $s^{-1}$, $\beta$=20$^0$: a) $R$=0.1 $m$, $f_R$=0.3;b) $R$=0.1 $m$, $f$=0.3; c) $f$=0.3, $f_R$=0.3

If the angular speed of rotation of the screw is increased, for example, to 30 $s^{-1}$, then the particle lift would be possible. The limit value of the coefficient of friction for this angular velocity is $f_R$=0.08. As the values of the angular velocity of rotation of the helical surface increase, the limit value of the coefficient decreases. Going to the boundary, the following is obtained:

$$\lim_{\omega \to \infty} \frac{g(f + \text{tg}\beta)}{R\omega^2(1 - f\,\text{tg}\beta)} = 0. \qquad (27)$$

Thus, if the surface of the cylindrical casing is absolutely smooth, then the lifting of the particle becomes impossible for any angular speeds of screw rotation.

Figure 3c shows the graphical dependence $\alpha'=\alpha'(R)$, from which it follows that the increase in the radius value R leads to an increase in the lifting speed, but it has a certain limit.

If the angle value $\beta$ is negative, the direction of winding the helical line changes, which means that with the same direction of the angular velocity of screw rotation, the particle on its surface will slide not up, but down. Transportation of the particle downwards has its own characteristics depending on the angle value $\beta$. If in equation (20) before the angle $\beta$ the sign is changed, then one of the expressions in parentheses will be written: $f\cos\beta-\sin\beta$. If the angle $\beta$ is equal to angular friction, i.e., $f=\mathrm{tg}\beta$, then this expression is converted to zero. To convert the entire equation (20) to zero, it is enough to equate another expression in parentheses to zero: $\omega-\alpha'=0$. The angular velocity of sliding of a material particle is equal to the angular velocity of rotation of the helical surface. Since they are directed in opposite directions, their sum is zero, that is, the particle in absolute motion does not rotate, but falls down in a straight line – the generating cylinder. Next, the study finds $\alpha'$ and $z'$ for three angles: smaller, larger, and equal angular friction $\beta f$ as with lifting the particle for $R=0.1$ *m*, $\omega=15$ $s^{-1}$and $f=f_R=0.3$.

$\beta<\beta_f$: $\beta=-10^0$; $\alpha'=8.8$ $s^{-1}$; $z'=-0.16$ *m/s*;
$\beta=\beta_f$: $\beta=-\mathrm{Arctg}f=-16.7^0$; $\alpha'=15$ $s^{-1}$; $z'=-0.45$ *m/s*;
$\beta>\beta_f$: $\beta=-20^0$; $\alpha'=20.4$ $s^{-1}$; $z'=-0.74$ *m/s*.

Figure 4 shows the relative and absolute trajectories of the particle's motion for these cases. Frontal projections of trajectories are shown at different scales.

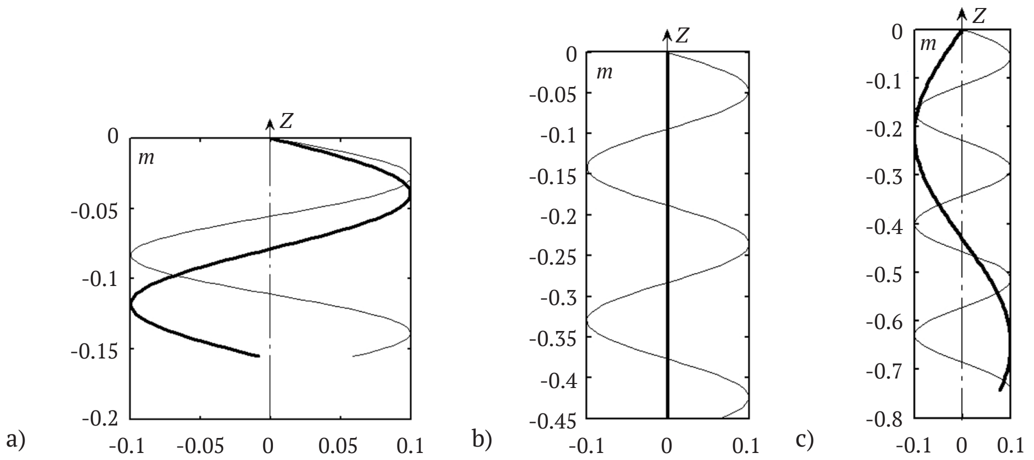


**Figure 4.** Trajectories of the particle's downwards movement at $R=0.1$ *m*, $\omega=15$ $s^{-1}$, $f=f_R=0.3$ during the time $t=1$ *s*: a) $\beta=-10^0$; b) $\beta=-$ Arctg$f=-16.7^0$; c) $\beta=-20^0$

By solving differential equation (20), the kinematic parameters of the motion of a material particle by numerical methods is found. Figure 5 shows graphical dependencies $\alpha'=\alpha'(t)$ and $z'=z'(t)$, which show the motion of the particle for 1.5 seconds. The angular velocity and velocity reach the values obtained earlier.

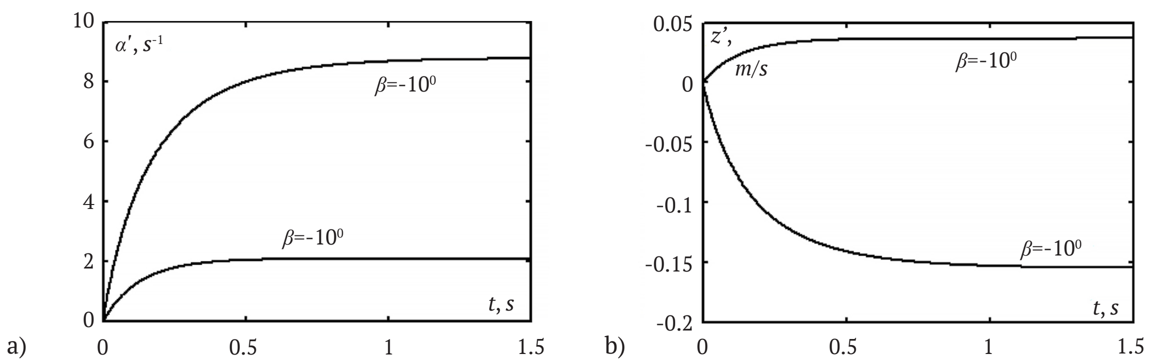


**Figure 5.** Graphical dependences of changes in the velocities of movement of a material particle at $R=0.1$ *m*, $\omega=15$ $s^{-1}$ and $f=f_R=0.3$: a) graphical dependency $\alpha'=\alpha'(t)$; b) graphical dependency $z'=z'(t)$

The process of overloading the flow of loose material would differ from the movement of a single particle, but it can be assumed that the qualitative picture of overloading the material will be the same.

In [15], it is proved that a material particle can move at different velocities when moving up in the conveyor. In addition, studies [16; 17] show that at the same angular velocity of rotation of a helical surface, the velocity of movement of a material particle up $z'_a$ will depend on the size of the tilt angle $\beta$ of a helical line. In [18], it is proved that after stabilisation of the movement of a material particle, the speed of movement of the material particle up and the angular sliding velocity $\alpha'$ material particles are constant values, and therefore, the angular acceleration value $\alpha''=0$ is zero. The value $\alpha'$ can be determined with the specified parameters of the helical surface, the angular velocity of its rotation, and the coefficients of friction [19]. Having solved the equations of motion of a material particle compiled in this paper by numerical methods, the resultscorresponding to the results given in are obtained [20]. It was also established that there was a change in the direction of movement of the material particle [21].

## CONCLUSIONS

As a result of the conducted theoretical studies, a mathematical model of the movement of a material particle by the working surface of a helical body, which is a screw and the surface of a limiting cylinder, is obtained.

As a result of solving differential equations by numerical integration, it is established that a particle falling on the surface of a vertical screw that moves around its axis is thrown back to a coaxial stationary limiting cylinder under the action of centrifugal force. Further movement of the particle occurs along the common line of these two surfaces – a helical line – with simultaneous sliding on both surfaces. The absolute movement of a material particle in the vertical direction occurs both up and down and depends on the angle $\beta$ tilt of the helical line of the screw and its angular rotation speed. The limiting value of the angle $\beta$ of inclination of the helical line, at which the lifting of the particle is impossible, and the value of the angle at which the value of the particle velocity is the greatest, is determined.

It is established that a decrease in the coefficient of friction of a particle on the helical surface leads to an increase in the speed of its movement up, and a decrease in the coefficient of friction of a material particle on the surface of the limiting cylinder leads to its decrease.

When changing the direction of winding the helical line, the particle can only be transported downwards at a much higher speed.

The prospect of this study is to establish the regularities of the movement of the material flow along the working surfaces of the helical body and the limiting cylinder and determine the energy and power parameters of transportation.

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**Сергій Федорович Пилипака[1], Микола Богданович Клендій[2]**

Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна

[2]Відокремлений підрозділ національного університету біоресурсів і природокористування України «Бережанський агротехнічний інститут», Україна
47501, вул. Академічна, 20, м. Бережани, Тернопільська область, Україна


# Транспортування частинки матеріалу робочим органом сільськогосподарської машини у вигляді вертикального шнека, обмеженого співвісним нерухомим циліндром


**Анотація.** Застосування в гвинтових конвеєрах вертикальних шнеків дозволяє суттєво розширити експлуатаційні можливості таких засобів механізації для виконання завантажувально-розвантажувальних технологічних операцій. Однак існуючі конструкції вертикальних шнеків не в повній мірі задовольняють експлуатаційні вимоги. Основними їх недоліками є підвищені енерговитрати, особливо при їх значних габаритних розмірах, які залежать від впливу тертя технологічного матеріалу по поверхнях конвеєра. Тому в статті розглянуто рух частинки матеріалу робочим органом сільськогосподарської машини у вигляді вертикального шнека, обмеженого співвісним нерухомим циліндром та встановлено залежність швидкості транспортування частинки матеріалу від впливу коефіцієнта тертя частинки по поверхні шнека та коефіцієнта тертя частинки по поверхні обмежуючого циліндра. Метою дослідження було визначення параметрів руху частинок сільськогосподарських матеріалів при їх взаємодії із гвинтовою поверхнею робочого органа вертикального конвеєра, виготовленого у вигляді шнека, який обертається навколо осі, та поверхнею співвісного нерухомого циліндричного кожуха. Математичне моделювання процесів руху частинок ґрунту по гвинтовій поверхні робочого органу описано на базі загальних законів і принципів аналітичної та диференціальної математики, теоретичної та аналітичної механіки. В результаті проведеного дослідження було складено диференціальні рівняння переміщення частинки сільськогосподарського матеріалу по гвинтовій поверхні шнека, який обертається навколо своєї осі у нерухомому циліндрі. Рівняння розв'язано за допомогою чисельних методів і побудовано траєкторії відносного руху частинки по гвинтовій лінії – крайці шнека, яка є спільною для поверхні шнека і обмежуючого циліндра. Також враховано сили тертя частинки матеріалу по поверхнях шнека і кожуха. Знайдено граничне значення кута підйому гвинтової лінії, коли підйом частинки стає неможливим при заданій кутовій швидкості обертання шнека. Виявлено вплив кутів тертя і радіуса обмежуючого циліндра на швидкість підйому частинки. Наведено графіки кінематичних характеристик у функції часу. Матеріали статті можуть бути використані науковцями для подальших досліджень та практиками у виборі конвеєрів для транспортування сільськогосподарських матеріалів



**Ключові слова**: конвеєр, гвинтова поверхня, кутова і лінійна швидкості, обмежуючий кожух, диференціальні рівняння руху, кінематичні параметри