The transportation of a particle by a vertical auger with a coaxial cylinder which rotate together around the common axis

Tatiana Volina¹*, Sergiy Pylypaka¹, Oleksandr Pavlenko², Oleksii Klochko³ and Iryna Hryshchenko¹

¹ National University of Life and Environmental sciences of Ukraine, 15 Heroyiv Oborony St., Kyiv 03041, Ukraine
² Bohdan Khmelnytsky Melitopol State Pedagogical University, 20 Hetmanska St., Melitopol 72300, Ukraine
³ Sumy State Pedagogical University named after AS Makarenko, 87 Romenskaya St., Sumy 40002, Ukraine

*E-mail: t.n.zaharova@ukr.net

Abstract. Differential equations of relative movement of a particle on the periphery of a vertical auger bounded by a movable coaxial cylinder are compiled. Both surfaces form a single whole and rotate around a common axis. A partial case, when the surfaces are stationary, is considered. A qualitative analysis of the obtained equations is made and on this basis, the regularities of the particle movement along the helical line – the curve of the intersection of the auger with the cylinder are found. Structural and kinematic parameters in which the particle moves upwards during sliding along the helical line, or falls downwards are found. The relative and absolute trajectories of the particle movement are constructed.

1. Introduction

To begin with, blades are used for the ordered movement of particles on the surface of rotation, which performs a rotational movement around the vertical axis. If a cone without blades, which rotates around its vertical axis, is taken, the particle will slide on it, rising at the same time up. Juicers, in which the cone is used as a sieve, work on this principle [1].

If the particle needs to be accelerated and to be given the desired direction of its leaving the cone, flat vertical blades are used. Actually, centrifugal scattering devices [2] work on this principle (figure 1,a). In this case, the trajectory of the relative movement of the particle is a straight line – the line of intersection of the cone and the blade.

In addition, there are juicers with a cylindrical sieve [3], but the crushed particles must be removed manually after squeezing the juice because they do not rise upward. Clearly, a possible variant for lifting the particle is to use a curved blade in the form of a strip of helical conoid – auger (figure 1,b). Lifting of technological material by augers inside a cylindrical casing is widely applied in various mechanisms, however, the cylindrical casing thus is motionless.

Based on the foregoing, the aim of this research was to investigate the laws of movement of material particles inside the construction, which is a single whole of the cylinder and the coaxial strip of the helical conoid, and which rotates around a common vertical axis.

2. Literature review

It is a well-known fact, that the movement of the technological material along the surface depends on the shape of this surface. To accurately describe the movement of a material along a surface, it is necessary to take into account inertia forces from its rotation, which is extremely difficult to do. Therefore, in many cases, these forces are neglected if body sizes or angular velocities of its rotation are small [4]. A great deal is being written and said about the fact, that particles of material in contact with
the surface may have a different origin: particles in a moving stream, mechanical particles, particles of a liquid or a gas [5, 6]. The movement of particles that are in contact with moving spiral working bodies, considered in the articles [7, 8]. Furthermore, the movement of particles on the surface of a rotating vertical helicoid is studied in [9]. In many cases, to simplify calculations, it is customary to consider the body as a material particle. The articles [10, 11] are the closest to the research topic. The first article [10] considers the movement of a particle along a gutter in the form of a helical surface under the action of its own weight. The second article [11] – the transportation of bulk material on the example of a single particle inside a vertical stationary cylinder by means of an auger rotating in this cylinder.

![Figure 1](image1.png)

**Figure 1.** Designs of devices for transportation of the particles, consisting of a combination of two surfaces: a) conical surface with flat vertical blades; b) cylindrical surface with a curved blade in the form of a strip of the helical conoid.

3. **Research methodology**

In the article [12] it is shown that when a particle moves under its own weight on the surface of a stationary vertical helical conoid, it moves away from its axis. This is due to the fact that the particle moves along a curved trajectory, resulting in a centrifugal force that causes the particle to move to the periphery. Thus, the particle will meet the surface of the cylinder. The common line of the conoid and the cylinder (the line of their intersection) is a helical line (in figure 1 it is shown in a thickened line). The particle will slide along this helical line, having simultaneous contact with the surface of the conoid (auger) and cylinder. Compilation of a mathematical model of particle movement begins with the parametrical equations of the helix – the trajectory of the relative movement of the particle. Due to the fact that in the absence of rotation of the surfaces the particle can move down under the action of its own weight, let us write the parametrical equations of the helix, the direction of the construction of which corresponds to the direction of the descent of the particle:

\[
x = R \cos \alpha; \quad y = R \sin \alpha; \quad z = -R \alpha \tan \beta,
\]

where \( R \) is the radius of the limiting cylinder (a constant value); \( \beta \) is the angle of the raising of the helix (a constant value); \( \alpha \) is the angle of rotation of the point of the helix around its axis (an independent variable).

When the particles move along the helical line (1), there are reaction forces \( N \) and \( N_R \), directed along the normal to the conoid and the cylinder (figure 1,b). To determine the direction of this normal, the equations of these surfaces should be known.
The surface of the auger is formed by a set of rectilinear generatrices which are parallel to the horizontal plane, one end of which passes through the helical line (1), and the other is directed to the axis of the auger. Based on the method of formation of the auger, let us write its parametrical equations:

\[ X = (R - u) \cos \alpha; \]
\[ Y = (R - u) \sin \alpha; \]
\[ Z = -R \tan \beta, \]

where \( u \) is the length of the rectilinear generatrix of the auger (the second independent variable of the surface).

Counting the length of the generatrix starts from the helix. When \( u = 0 \) the parametrical equations of the helix (1) are obtained. To make the surface equations different from the line equations, lowercase letters are used for the line and uppercase letters – for the surface.

The vertical auger rotates around its axis with an angular velocity \( \omega \). The particle is located on the helical line (1) and is simultaneously in contact with the moving surfaces of the auger and cylinder (figure 1,b). The following forces are applied to it: the force of weight \( mg \) (\( m \) is the mass of a particle, \( g = 9.81 \text{ m/s}^2 \) is an acceleration of gravity), reaction \( N \) of a conoid, which is directed along normal to its surface, reaction \( N_R \), which is directed along normal to a surface of the cylinder, and the friction force \( F \) (figure 1,b). Assume that at \( \omega = 0 \) and at a sufficient value of the angle \( \beta \) the particle slides down, then the friction forces on the surface of the auger \( F_a \) and on the surface of the cylinder \( F_c \) are directed in the opposite direction of the sliding \( V \). The vectors of these forces will be tangent to the trajectory of relative movement (the helical line along which the particle slides), so \( F = F_a + F_c \).

The equation of movement should be composed in the form \( m \ddot{a} = \bar{F} \) where \( m \) is the mass of the particle, \( \ddot{a} \) is the vector of absolute acceleration, and \( \bar{F} \) is the resulting vector of the forces applied to the particle, which were listed earlier. The vector equation is described in projections on the coordinate axis \( OXYZ \).

If in equations (1) the variable \( \alpha \) is taken as time-dependent \( t (\alpha = \alpha(t)) \) then this internal dependence will specify the law of sliding of the particle along the helix (the law of relative movement). Therefore, under this condition, equations (1) are equations of relative movement.

The auger with the cylinder rotates around its axis with an angular velocity \( \omega \). During time \( t \), they rotate at the angle \( \alpha = -\omega t \) and move along the helix by a certain distance according to equations (1). The direction of rotation of the auger with the cylinder is selected so that the particle during sliding along the helix could rise in absolute movement. Let us rotate the helix (1) around the axis \( OZ \) at the angle \( \alpha = -\omega t \) according to the known formulas of rotation:

\[ x_u = R \cos \alpha \cos(-\omega t) - R \sin \alpha \sin(-\omega t) = R \cos(\omega t - \alpha); \]
\[ y_u = R \cos \alpha \sin(-\omega t) + R \sin \alpha \cos(-\omega t) = -R \sin(\omega t - \alpha); \]
\[ z_u = -R \tan \beta, \]

The parametrical equations (3) take into account two rotations: at the angle \( \alpha = \alpha(t) \) in relative movement and at the angle \( \alpha = -\omega t \) in transient motion, so they are the equations of absolute movement of the particle.

The equations (3) should be differentiated by the time \( t \) and projections of the absolute velocity vector can be obtained:

\[ \dot{x}_u = -R(\omega - \dot{\alpha}) \sin(\omega t - \alpha); \]
\[ \dot{y}_u = -R(\omega - \dot{\alpha}) \cos(\omega t - \alpha); \]
\[ \dot{z}_u = -R \dot{\alpha} \tan \beta. \]  

By differentiating equations (4) the projections of the absolute acceleration \( \bar{w} \) of the particle can be received:
\[ \dot{x}_a = R\alpha \sin(\omega t - \alpha) - R(\omega - \dot{\alpha})\cos(\omega t - \alpha); \]
\[ \dot{y}_a = R\alpha \cos(\omega t - \alpha) + R(\omega - \dot{\alpha})\sin(\omega t - \alpha); \]
\[ \dot{z}_a = -R\tan \beta. \]  

(5)

To decompose the vector equation \( \ddot{\mathbf{a}} = \ddot{\mathbf{F}} \) in the projections on the axis of the coordinate system \( OXYZ \), the direction of the forces \( F_a + F_c \) should be determined (figure 1, b). They are directed in the opposite direction of the vector of relative velocity \( \mathbf{V}_R \). Projections of this vector are found by differentiation equations (1):

\[ \dot{x} = -R\alpha \sin \alpha; \]
\[ \dot{y} = R\alpha \cos \alpha; \]
\[ \dot{z} = -R\tan \beta. \] 

(6)

The relative velocity \( \mathbf{V}_R \) of the movement of the particle is found:

\[ \mathbf{V}_R = \sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2} = \frac{R\alpha}{\cos \beta}. \] 

(7)

The projections of the unit directing vector of the relative velocity are found by dividing the projections (6) of this velocity by its absolute value (7):

\[ V_{xR} = -\cos \beta \sin \alpha; \quad V_{yR} = \cos \beta \cos \alpha; \quad V_{zR} = -\sin \beta; \] 

(8)

In fact, the projections of the vector (7) are written without taking into account the rotational movement of the helix. All forces are projected on the fixed coordinate system \( OXYZ \). In order for the force \( F_a + F_c \) to be applied at the point of location of the particle, the projections (8) must be rotated at an angle \( (\omega t) \) around the axis \( Oz \). After that, they take the form:

\[ \begin{bmatrix} \cos \beta \sin(\omega t - \alpha); & \cos \beta \cos(\omega t - \alpha); & -\sin \beta \end{bmatrix}. \] 

(9)

Let us find the direction of action of the reaction forces of the surfaces of the auger and cylinder. The direction of the normal to the surface is determined by the vector product of two vectors passing through a point on the surface (the point where the particle is located) and tangent to the coordinate lines passing through this point. The vector of the normal to the surface of the auger should be found, i.e. at \( u=0 \).

The vectors tangent to the coordinate lines of the surface are partial derivatives of equations (2) of the auger:

\[ \frac{dX}{du} = -(R-u)\sin \alpha; \quad \frac{dX}{du} = -\cos \alpha; \]
\[ \frac{dY}{du} = (R-u)\cos \alpha; \quad \frac{dY}{du} = -\sin \alpha; \]
\[ \frac{dZ}{du} = -R\tan \beta; \quad \frac{dZ}{du} = 0. \] 

(10)

Therefore, the vector product of vectors (10) is:

\[ \begin{bmatrix} X & Y & Z \\ -(R-u)\sin \alpha & (R-u)\cos \alpha & -R\tan \beta \\ -\cos \alpha & -\sin \alpha & 0 \end{bmatrix} = \begin{bmatrix} R\tan \beta \sin \alpha; & R\tan \beta \cos \alpha; & R-u \end{bmatrix}. \] 

(11)

The normal vector (11) is not a unit one. Its position on the surface is determined by two internal coordinates: \( u \) and \( \alpha \). The normal to the surface of the auger on the helical line at the location of the particle should be known, i.e. at \( u=0 \). Obviously, it is necessary to substitute \( u=0 \) in the expression of the vector (11) and to reduce it to a unit one.
Similarly, the normal to the cylindrical casing can be found. However, its projections can be found much easier. From figure 1, it would be seen that the normal to the cylinder is parallel to the horizontal plane and directed to its axis. The result can be obtained:

\[
\{-\cos \alpha; -\sin \alpha; 0\}. \tag{13}
\]

Due to the above reasons, the unit vectors (12), (13) should be rotated at the angle \((-\omega t)\). After that, the unit vector of the normal to the surface of the auger at the location of the particle will be written:

\[
\{\sin \beta \sin (\omega t - \alpha); \sin \beta \cos (\omega t - \alpha); \cos \beta\}. \tag{14}
\]

The unit vector of the normal to the cylindrical casing (13) after rotation at an angle \((-\omega t)\) takes the form:

\[
\{0; \sin (\omega t - \alpha); 0\}. \tag{15}
\]

Doubtless, the directions of action of the applied forces are defined: for the friction force \(F_{\alpha} + F_{\beta}\) by a unit vector (8), taken with the opposite sign; reactions of the surfaces \(N\) of the auger and \(N_0\) of the cylindrical casing – by unit vectors (14) and (15), respectively. The last force (the force of gravity of the particle \(mg\)) is directed downwards, so the unit vector is given by projections:

\[
\{0; 0; -1\}. \tag{16}
\]

The value of the friction forces \(F_{\alpha}\) and \(F_{\beta}\) is determined by the value of the surface reaction and the corresponding coefficient of friction: \(F_{\alpha} = fN\), \(F_{\beta} = f_k N_k\), where \(f\) and \(f_k\) are the coefficients of friction of the particle on the surface of the auger and of the cylindrical casing, respectively. Therefore, the friction force \(F = F_{\alpha} + F_{\beta} = fN_k + fN\).

Hence, the vector equation \(m\ddot{a} = \vec{F}\) should be decomposed in the projections on the axis of the coordinate system \(OXYZ\) taking into account the directions (9), (14), (15), (16) and the corresponding forces \(F = fN_k + fN\), \(N, N_0\) and the force of weight \(mg\):

\[
\begin{align*}
\dot{x}_a &= -(f_{N_k} + fN) \cos \beta \sin (\omega t - \alpha) + N \sin \beta \cos (\omega t - \alpha) - N_{R_k} \cos (\omega t - \alpha); \\
\dot{y}_a &= -(f_{N_k} + fN) \cos \beta \cos (\omega t - \alpha) + N \sin \beta \cos (\omega t - \alpha) + N_{R_k} \sin (\omega t - \alpha); \\
\dot{z}_a &= (f_{N_k} + fN) \sin \beta + N \cos \beta - mg.
\end{align*}
\]

By substitution in (17) the expressions of absolute acceleration from (5) a system of three differential equations with three unknown functions: \(a = a(t), N = N(t)\) and \(N_0 = N_0(t)\) can be obtained. Let us solve the system regarding \(\dot{a}, N, N_0\):

\[
\dot{a} = \frac{g \cos \beta}{R} (\sin \beta - f \cos \beta) - f_{\beta}(\omega - \dot{a})^2 \cos \beta \tag{18}
\]

\[
N = m \cos \beta. \tag{19}
\]

\[
N_R = mR(\omega - \dot{a})^2. \tag{20}
\]

The differential equation (18) does not depend on (19) and (20), so it can be solved separately, after which reactions (19) and (20) can be found. Furthermore, equation (18) has an analytical solution, but even without a solution, some important conclusions can be done based on its qualitative analysis.

Generally, it can be assumed that over time the movement of the particle stabilizes, so the angular sliding velocity \(\dot{a}\) will be constant and the acceleration is \(\dot{a} = 0\). After substitution in (18) \(\dot{a} = 0\) and solving regarding \(a\) the expression can be obtained:
\[
\dot{\alpha} = \omega ± \left[ \frac{g}{Rf} (\sin \beta - f \cos \beta) \right]^{1/2}
\]

(21)

4. Results

It can be concluded that if the surfaces are stationary (\(\omega=0\)), then the sliding of the particle is possible, provided that the subroot expression is greater than zero. It becomes equal to zero at \(f=\tan \beta\). This means that the angle of elevation of the helix is equal to the angular friction of the particle on the surface of the cone. If an angle \(\beta\) is less than the angle of friction, the particle does not slide on the surfaces of both stationary and moving. During the rotation of the surfaces with an angular velocity \(\omega\), the particle is pressed under the action of centrifugal force to the cylinder and rotates with it, i.e. “sticks”. The turning point occurs when the angle \(\beta\) is greater than the angle of friction. In this case, the particle will move down on stationary surfaces with an angular velocity, the value of which is determined by the square root of expression (21).

Indeed, if the surfaces have an angular velocity \(\omega\), then the angular velocity of the relative movement \(\dot{\alpha}\) of the particle will be determined by the formula (21) with the sign “\(-\)" before the root, i.e. the difference between the angular velocity of rotation of the surfaces and the angular velocity of the particle sliding along the stationary surfaces. Let us denote \(\omega_j = \left[ \frac{g (\sin \beta - f \cos \beta)}{Rf} \right]^{1/2}\) and then write:

\[
\dot{\alpha} = \omega - \omega_j
\]

where \(\omega_j\) is the velocity of sliding of the particle on stationary surfaces. For \(\omega < \omega_j\), \(\dot{\alpha}\) will be negative and the particle will fall down. As the angular velocity \(\omega\) of the surface rotation increases, the lowering velocity will decrease. When the angular velocities become equal (\(\omega=\omega_j\)), the particle “sticks”. Besides, with a further increase of the angular velocity \(\omega\) (i.e., at \(\omega > \omega_j\)), the particle will rise, and the velocity of the raising will be directly proportional to the difference \(\omega - \omega_j\). Thus, the transportation of the particle up is impossible under three conditions: 1) the angle \(\beta\) of the raising of the helical line is less than the angle of friction – the particle “sticks”; 2) the angle \(\beta\) is greater than the angle of friction, \(\omega < \omega_j\) – the particle is descending; 3) the angle \(\beta\) is greater than the friction angle, \(\omega = \omega_j\) – the particle “hangs”, i.e. the angular velocities of the rotation of the surfaces and the sliding of the particle are equal in value and opposite in sign and the absolute velocity of rotation is equal to zero.

As a consequence, note some differences in the movement of the particle on an inclined plane and on the described surfaces, when \(f=\tan \beta\), i.e. the angle of inclination of the plane and the angle of the raising of the helix are equal to the angle of friction. In this case, the particle will move on the plane with a constant velocity \(V_r\), the value of which is set at the beginning of the movement. The particle on stationary surfaces will not move, because a centrifugal force arises, which causes the appearance of friction force. However, if the surface of the cylinder is absolutely smooth (i.e. \(f_k=0\)), then according to the differential equation (18) the movement of the particle on the surfaces is also possible with a given constant velocity \(V_k\). If \(f_k\neq0\), then the particle on a stationary surface will remain at rest, and if you give it the initial velocity \(V_k\), then over time it will stop. Moreover, if the surfaces are given the angular velocity \(\omega\), the particle can be either in the “sticking” mode or in the “hanging” mode. The “sticking” mode corresponds to the initial velocity \(V_k=0\). The “hanging” mode corresponds to such initial velocity \(V_k\), which will provide an angular velocity of the sliding of the particle is equal to the angular velocity of the rotating of the surfaces. Then the absolute angular velocity of rotation of the particle is equal to zero and according to (20) the reaction \(N_k\) of the cylinder is absent, therefore, there is no corresponding friction force in equation (18).

As was already mentioned, the case (\(\omega=\omega_j\)) is the boundary between the lowering and raising of the particle. Moreover, at \(\omega < \omega_j\) the particle is moving down, at \(\omega > \omega_j\) the particle is moving up. When \(\omega = \omega_j\) the height of location of the particle does not change, and it can be both in the mode of “sticking” and in the mode of “hanging”.

It should be noted that the relative and absolute trajectories of the particle movement were constructed by equations (1) and (3). Let the coefficient of friction \(f=0.3\). It corresponds to the angle of
friction $\beta=\arctan f=16.7^\circ$. In order to avoid sticking, the lifting angle of the helix must be greater than the angle of friction. Assume $\beta=20^\circ$. At $R=0.1$ m, $f_R=0.3$ it can be found: $\omega_0 = \frac{g\left|\sin \beta - f \cos \beta\right|}{Rf_R}^{1/2} = 4.43$ s$^{-1}$. It is the angular velocity of the descent of the particle on fixed surfaces ($\omega=0$). It can be seen, that the relative and absolute trajectories coincide (figure 2,a). In figure 2,b the relative and absolute trajectories at $\omega=2$ s$^{-1}$ are constructed. The particle descends, but the velocity of descent has decreased. It is clear, that at $\omega=\omega_0$ the movement of the particle in the vertical direction is absent at all. In figure 2,c the relative and absolute trajectories at $\omega=10$ s$^{-1}$ are constructed. The particle rises and with increasing $\omega$ the velocity of the raising increases proportionally.

Accordingly, in figure 2,d relative and absolute trajectories with the previous parameters and a reduced coefficient $f_R=0.2$ are constructed. The velocity of the particle raising decreased as the value of $\omega_0$ was changed. With a further decrease in $f_R$, the raising may change to lowering, and at $f_R=0$ the particle will move down uniformly accelerated.

The reaction of the surface of the auger (19) and the cylinder (20) are constant. By substituting in (20) $\dot{\alpha} = \omega - \omega_0$, one can obtain: $N_R = mR\omega_0^2$. Therefore, the value of the reaction of the cylinder does not depend on the angular velocity of its rotation and is determined by the angular velocity of the particle sliding on fixed surfaces.

5. Conclusions

If the angle of the raising of the helical line (the curve of the intersection of the cylinder with the helical conoid) is less than the angle of friction of the particle on the conoid, then the transportation of the particle is impossible both up and down. This applies to both stationary and movable surfaces that rotate around a common axis. The particle rotates together with the surfaces, i.e. “sticks”. If the angle of the raising of the helical line is equal to the angle of friction, then transportation is also impossible and the particle can either “stick” or “hang”. The last variant means that the particle slides along the helical line with an angular velocity of the rotation of the surfaces, but the angular velocities have the opposite sign. In absolute movement, the particle remains stationary. The mode of “sticking” or “hanging” depends on the initial conditions.

If the angle of the raising of the helix is greater than the angle of friction, the transportation of the particle is possible both up and down. In this case, the angular velocity $\omega_0$ of the particle during its descent on fixed surfaces is important. If the angular velocity $\omega$ of surface rotation is less than $\omega_0$, then the particle will move downwards. As $\omega$ increases, the velocity of the descent of the particle will decrease. When $\omega=\omega_0$, the particle “hangs”, when $\omega>\omega_0$ it moves upwards. The velocity of the raising
of the particle is directly proportional to the increase of the angular velocity $\omega$ of the rotation of the surfaces. Prospects of further researches are the experimental verification of obtained theoretical results.

References
[1] Changzhong Wu, Fan Ge, Guangchao Shang, Guitaow Wang, Mingpeng Zhao, Liang Wu and Hengshuai Guo 2021 Design of screw type automatic apple juicer *Journal of Physics: Conference Series* **1750** 012042

[2] Zhilenko D, Krivonosova O and Gritsevich M 2019 New type of centrifugal instability in a thin rotating spherical layer *Journal of Physics: Conference Series* **1163** 012011-1-012011-5

[3] Arema, Ademola K and Ogunlade Clement A 2016 Development and evaluation of a multipurpose juice extractor *New York Science Journal* **9(6)** pp 7–14

[4] Liaposchenko O, Pavlenko I and Nastenko O 2017 The model of crossed movement and gas-liquid flow interaction with captured liquid film in the inertial-filtering separation channels *Separation and Purification Technology* **173(1)** pp 240–243

[5] Golub G, Szalay K, Kukharets S and Marus O 2017 Energy efficiency of rotary digesters *Progress in Agricultural Engineering Sciences* **13(1)** pp 35–49

[6] Kobets A, Ponomarenko N and Kharytonov M 2017 Construction of centrifugal working device for mineral fertilizers spreading *INMATEH–Agricultural Engineering* **51(1)** pp 5–14

[7] Trokhaniak O, Hevko R, Lyashuk O, Dovbush T, Pohrishchuk B and Dobizha N 2020 Research of the of bulk material movement process in the inactive zone between screw sections *INMATEH–Agricultural Engineering* **60(1)** pp 261–268

[8] Hevko R, Zalutskyi S, Hladyo Y, Tkachenko I, Lyashuk O, Pavlov O, Pohrishchuk B, Trokhaniak O and Dobizha N 2019 Determination of interaction parameters and grain material flow motion on screw conveyor elastic section surface *INMATEH–Agricultural Engineering* **57(1)** pp 123–134

[9] Pavlenko I, Liaposchenko A, Ochowiak M and Demyanenko M 2018 Solving the stationary hydroaeroelasticity problem for dynamic deflection elements of separation devices *Vibrations in Physical Systems* **29(2018026)**

[10] Pylypaka S, Nesvidomin V, Zaharova T, Pavlenko O and Klendiy M 2020 The investigation of particle movement on a helical surface *Lecture Notes in Mechanical Engineering* pp 671–681

[11] Nnamdi U, Onyejiuwa C and Ogbuke C 2020 Review of orange juice extractor machines *Advances in Science, Technology and Engineering Systems Journal* **5(5)** pp 485–492

[12] Pylypaka S F, Klendii M B and Klendii O M 2017 Particle motion over the surface of a rotary vertical axis helicoid *INMATEH–Agricultural Engineering* **51(1)** pp 15–28