MATHEMATICAL MODELING AND OPTIMIZATION OF THE WORKING PROCESS OF A SPIRAL-TYPE CUTTER FOR SAPROPEL EXTRACTION

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ABSTRACT

The article presents an analytical overview demonstrating the feasibility of using pneumatic (airlift) sapropel extraction machines designed to obtain organic sapropel raw material – a fundamental component in the production of fertilizers for organic farming. The section State of the Art and Problem Statement highlights the shortcomings of the existing mechanical adjustment and control systems of such machines, which are often inefficient and prone to operational failures. Since pneumatic sapropel extraction systems have proven to be energy-efficient and environmentally sustainable in obtaining organic raw materials and are currently undergoing active modernization, a comprehensive automated system was proposed as the result of this research. The developed system simultaneously performs several functions – it forecasts, adjusts, and controls the machine's operating process. The system determines and configures the optimal technological parameters of the workflow and automatically monitors, modifies, and manages them depending on the unpredictable characteristics and properties of the sapropel deposit. It also forecasts potential changes in the operating process and structural loads that may lead to machine failure, thereby preventing such occurrences. The paper presents a block diagram illustrating the sequence of processes for forecasting, adjustment, and control of airlift sapropel extraction machines, as well as the layout of information and control devices that implement the operational process. The proposed system will increase the efficiency of machine operation, ensure uniform extraction of sapropel layers, and provide high-quality raw material with minimal impact on the aquatic ecosystem.

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ОБГРУНТУВАННЯ КІНЕМАТИКИ РОБОЧОГО ОРГАНУ ФРЕЗЕРНОЇ СИСТЕМИ ДОБУВАННЯ САПРОПЕЛЮ

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АНОТАЦІЯ

У статті представлено результати аналітичного дослідження руху матеріальної точки по поверхні спіралі Архімеда, яке використано як основу для побудови математичної моделі робочого процесу транспортування сапропелю спіральним робочим органом. Робота спрямована на обґрунтування конструктивно-технологічних параметрів спіральних систем, що застосовуються у технологічних засобах для добування та переміщення сапропелевої маси з дна водойм. У процесі дослідження виконано аналітичний опис кінематичних залежностей для руху частинок в'язкопластичного середовища вздовж спіральної траєкторії, визначено вплив геометричних параметрів спіралі, кутової швидкості обертання та сил опору на характер переміщення матеріалу. Запропонована модель може бути адаптована для аналізу процесів транспортування інших вологих і в'язких матеріалів (мулу, торфу, осадів стічних вод, волокнистих сумішей) шляхом введення коефіцієнта матеріальної подібності, який враховує густину, вологість і реологічні властивості середовища. Отримані результати можуть бути використані при проектуванні робочих органів машин для добування сапропелю, а також у системному аналізі технологічних процесів, де необхідне моделювання руху частинок у спіральних каналах або гвинтових транспортерах.

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STATE OF THE ART AND ANALYSIS OF PUBLICATIONS

One of the promising directions in improving technologies for extraction and processing of organic bottom sediments is the use of spiral conveying systems, particularly working bodies in the form of an Archimedes spiral (Molchak, 1998; Shevchuk, 2012). Such designs ensure stable movement of viscoplastic materials in a confined environment and are energy-efficient due to the combination of transport, dosing, and partial dewatering functions. Modern developments in the field of hydromechanized sapropel extraction indicate the need for a deeper theoretical analysis of the process of particle movement along curved surfaces, which determines the productivity and stability of the extraction equipment (Didukh, 2016).

Given the increasing demand for environmentally safe fertilizers and the rational use of natural resources, the issue of effective extraction and transportation of lake sapropels – valuable organic raw materials for agricultural production – is becoming particularly relevant (Tsyz, 2020; Khomych, 2021). The development of technological systems for sapropel extraction requires consideration of their physical-mechanical and rheological properties, as well as the construction of models describing the kinematics and dynamics of material movement during transportation.

An analysis of scientific publications shows an insufficient number of theoretical works devoted to modeling the motion of a material point along a spiral surface, especially under the action of Archimedes' buoyant force in an aquatic environment (Khlopetskyi, 2024). Most studies focus on the constructive aspects of conveyors or hydraulic systems, but lack a systematic approach to the mathematical description of the working process of a spiral mechanism that moves viscous material along its axis (Tsyz et al., 2025).

The mechanization of sapropel extraction and feed processes has been studied in the works of Tsyz I.Ye., Didukh V.F., and Khomych S.M. (2025), where the authors analyzed the operating process of a pneumo-mechanical device for sapropel extraction. They established the relationship between the transport velocity of the mixture and the parameters of bubble lifting, emphasizing the feasibility of automated air supply regulation and pipeline inclination angle adjustment to stabilize system productivity.

Didukh V.F., Tsyz I.Ye., and Holii O.V. (2023) investigated the influence of natural-moisture sapropel on soybean yield under moisture deficit conditions, emphasizing the importance of preparing raw materials of proper consistency for subsequent agrotechnological use. These works outlined the range of technological and technical problems related to sapropel transportation from the extraction site to the accumulation zone.

Earlier, Didukh (2016) studied the dynamics of the excavation process of lake sapropels from under a water layer, describing the nature of force interactions between the intake device and sapropel mass and demonstrating the influence of the working body's entry angle into the deposit on the stability of the hydraulic system.

However, in most studies, the research focuses either on the structural aspects of machines or on experimental efficiency indicators, without systematic mathematical modeling of particle motion in spiral or screw channels (Tsyz & Didukh, 2023; Khomych, 2021). This creates a scientific gap in understanding the kinematics and dynamics of material flow in spiral working bodies.

Constructing an analytical model of particle motion along an Archimedes spiral will allow obtaining generalized dependencies between the spiral's geometric parameters, rotation frequency, resistance forces, and energy consumption of the process.

Introducing a coefficient of material similarity makes it possible to adapt the model for other types of viscous and fibrous materials – such as sludge, peat, wastewater sediments, or technical pastes – thus increasing the universality of the results for analyzing technological systems of various purposes.

ESEARCH PURPOSE AND OBJECTIVES

The purpose of the study is to develop a mathematical model of the motion of a viscoplastic material particle along the surface of an Archimedes spiral, taking into account the geometric and kinematic parameters of the working body used for sapropel transportation.

To achieve this goal, the following objectives were set:

– to analyze the physical and mechanical properties of sapropel as an object of transportation;

– to construct analytical dependencies describing the trajectory of a material point moving along a spiral under the influence of hydrostatic and frictional forces;

– to determine the influence of the spiral's geometric parameters on the uniformity of motion and the efficiency of transportation;

– to justify the applicability of the obtained model to other types of viscous media by introducing a material similarity coefficient.

Additionally, the research aims to design a system for automated forecasting, adjustment, and control of the working process in airlift-type sapropel extraction machines, in order to obtain high-quality raw material, increase productivity, and prevent equipment failures under unpredictable deposit characteristics and material properties.

MATERIALS AND METHODS

To study the process of sapropel transportation within the spiral working body, an analytical approach was applied using methods of mathematical modeling of a material point moving along the curved surface of an Archimedes spiral.

A blade in the form of a spiral sector rotating in a vertical plane with a constant angular velocity was considered. At the initial moment, a material point of mass *m* is located on the inner surface of the spiral and is subjected to gravitational force, sliding friction, and the buoyant force of Archimedes, which is proportional to the difference between the densities of sapropel and water. The friction coefficient is determined experimentally, depending on the moisture content and consistency of the sapropel mass.

The mathematical model of particle motion is described by a system of differential equations that accounts for changes in coordinates in a polar system and the action of buoyant force. To ensure the stability of the solution, the model was implemented numerically using the Runge–Kutta method of the 4th order. Calculations were performed in the MathLab environment, which made it possible to obtain graphical dependencies of:

– the angular position of the particle over time;
– relative angular velocity;
– trajectory of particle movement in absolute coordinates.

The input parameters of the model included the geometric characteristics of the spiral (radius, pitch, inclination angle), sapropel density, water density, friction coefficient, and rotational frequency of the working body. Parameters were determined considering typical sapropel extraction conditions of medium moisture content at depths of 3–5 meters.

To evaluate the influence of design parameters on transportation efficiency, dimensionless similarity coefficients were used, allowing the generalization of results for other types of viscoplastic media such as sludge, wastewater sediments, or peat suspensions.

The obtained dependencies made it possible to estimate the effect of rotation frequency on the stability of material point motion: a stable regime is achieved when the rotation frequency of the spiral working body increases from 15 to 25 rpm, which corresponds to experimental observations of effective sapropel mass movement.

The proposed approach can be applied for the calibration of parameters of similar transport systems when processing other natural materials using the coefficient of material similarity.

RESULTS AND DISCUSSION

Problem formulation.

A planar curve lying in a vertical plane, given in polar coordinates by its graph $r = r(\varphi)$ with $\frac{dr}{d\varphi} \le 0$ for $0 < \varphi < \frac{\pi}{2}$, rotates in its plane clockwise with constant angular velocity ω. At the initial time $t = 0$, a material point of mass m is placed at some point of the curve and is initially at rest with respect to an absolute inertial frame. The coefficient of sliding friction between the point and the curve is μ. Gravitational acceleration is *g*.

The point is also subjected to the Archimedes buoyant force proportional to the weight of the displaced fluid, i.e.

$$F_b = \rho_w \cdot g \cdot V \, ,$$

where ρ_s is the density of sapropel (the particle/material), ρ_w is the density of water, and *V* is the displaced volume (so that $m = \rho_s V$).

Required: derive the equations of motion of the material point on the rotating curve.

Notation recap:

- $r(\varphi)$: polar equation of the curve, vertical plane;
- ω: constant angular speed of the curve (clockwise);
- m, μ, g : mass, friction coefficient, gravity;
- ρ_s, ρ_w, V : sapropel density, water density, displaced volume;
- $F_b = \rho_w \cdot g \cdot V$ (buoyancy).

Remark: it is often convenient to write the effective weight acting downward as

$$W_{eff} = (\rho_s - \rho_w) \cdot g \cdot V = m \cdot g \cdot (1 - \frac{\rho_w}{\rho_s}),$$

while retaining F_b explicitly when projecting forces along the curve's tangent/normal.

SOLUTION OF THE PROBLEM

We assume that the material point does not detach from the curve; therefore we analyze its motion in a non-inertial reference frame rigidly attached to the given curve. The origin of this frame is placed at a fixed point *O*. Since the trajectory is specified in polar coordinates, we introduce the standard orthonormal basis vectors e_r and e_φ, directed along the radius vector of the point and perpendicular to it in the direction of increasing polar angle φ, respectively (see Fig. 1).

According to (Tsyz et al., 2023), the kinematic relations for the polar basis are:

$$\dot{e}_r = \dot{\varphi} e_\varphi,$$

$$\dot{e}_\varphi = -\dot{\varphi} e_r.$$

In addition, we introduce the unit vectors of the natural (Frenet) frame along the trajectory: the tangent *t* and the normal *n* (the normal points toward the center of curvature, i.e., in the direction of greatest concavity of the path). These vectors are related to e_r and e_φ by:

$$t = \frac{\partial r / \partial \varphi}{\left\| \partial r / \partial \varphi \right\|},$$

$$n = \frac{Jt}{\| Jt \|},$$

where $r = r(\varphi)\mathbf{e}_r$ is the position vector of the point on the curve, and *J* is the planar rotation by $+\pi / 2$ (the Jacobian operator that maps a vector to one rotated by 90°in the positive sense), i.e. $J \cdot e_r = e_\varphi$ and $J \cdot e_\varphi = -e_r$.

Equivalently, using scalar components (prime denotes differentiation with respect to the variable indicated in the subscript), we can write

$$\frac{\partial \varphi}{\partial r} = r_\varphi^{'} \cdot e_r + r(\varphi) \cdot e_\varphi,$$

$$t = \frac{r_\varphi^{'} \cdot e_r + r \cdot e_\varphi}{\sqrt{(r_\varphi^{'})^2 + r^2}},$$

$$n = \frac{-r \cdot e_r + r_\varphi^{'} \cdot e_\varphi}{\sqrt{(r_\varphi^{'})^2 + r^2}}$$

Here $r_\varphi^{'} \equiv \frac{dr}{d\varphi}$. These relations will be used to project forces (gravity reduced by buoyancy, friction) and the non-inertial terms due to rotation with angular speed ω onto *t* and *n* when deriving the equations of motion.

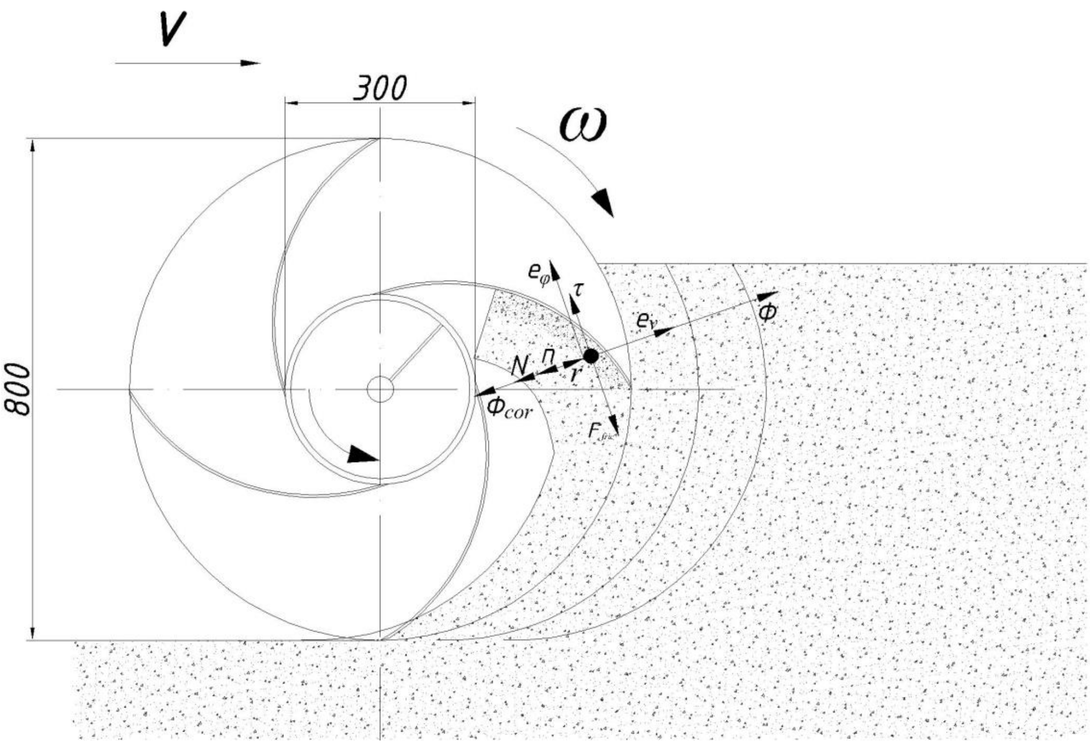

Figure 1 – Diagram of the forces acting on a material point moving along a curved surface

RESULTS AND DISCUSSION

Problem solution. We assume that the material point does not detach from the curve; therefore, we consider its motion in a non-inertial reference frame rigidly attached to the given curve. The origin of this frame is placed at a fixed point *O*. Since the trajectory is specified in polar coordinates, we introduce the unit orthogonal vectors e_r and e_φ, directed, respectively, along the radius vector of the point and perpendicular to it in the direction of increasing polar angle φ (see Fig. 1).

According to (Tsyz et al., 2023), $\dot{e}_r = \dot{\varphi} e_\varphi$, $\dot{e}_r = -\dot{\varphi} e_\varphi$. In addition, we introduce the unit vectors of the natural (Frenet) frame: the normal *n*, directed toward the greatest concavity of the trajectory, and the tangent *t*. These vectors are related to e_r and e_φ by

$$t = \frac{\partial r / \partial \varphi}{\left\| \partial r / \partial \varphi \right\|},$$

$$n = \frac{Jt}{|| Jt ||},$$

where *J* is the Jacobian (rotation by +π/2); primes denote derivatives with respect to the variable shown in the subscript, i.e., $r'_\varphi \equiv \frac{dr}{d\varphi}$.

Figure 1. Scheme of the forces acting on a material point moving along a curvilinear surface.

The relative velocity of the material point, by definition (Molchak et al., 1998), is

$$v_{rel} = \dot{s} \cdot t \tag{1}$$

where $\dot{\varphi}$ is the time derivative of the polar angle φ that specifies the position of the material point along its trajectory.

According to (1) and definition (Molchak et al., 1998), the relative acceleration of the material point is

$$a_{rel} = \ddot{s} \cdot t + \frac{\dot{s} \cdot 2}{\rho} \cdot n \tag{2}$$

where $\kappa = 1/\rho$ is the curvature and ρ is the radius of curvature of the trajectory.

The transport (convective) acceleration (i.e., the acceleration due to the rotation of the coordinate system together with the curve) for the material point equals

$$a_{tr} = -\omega \cdot (\omega \cdot r) \tag{3}$$

and is directed toward the center O of rotation, since the angular acceleration of the frame rigidly attached to the curve is zero under the problem statement $(\dot{\omega} = 0, \alpha = 0)$.

The Coriolis acceleration of the material point is computed taking into account that the transport angular velocity vector is ω (per the problem statement). Hence, by definition (Molchak et al., 1998), the Coriolis acceleration is

$$a_{cor} = 2\omega \cdot v_{rel} \tag{4}$$

Thus, according to (3) and (4) and D'Alembert's principle (Molchak et al., 1998), the corresponding inertia forces are:

$$\begin{aligned} F_{tr} &= -m \cdot a_{tr}, \\ F_{cor} &= -m \cdot a_{cor}. \end{aligned} \tag{5}$$

In addition to the inertia forces (5), the material point is acted upon by the normal reaction of the constraint (the curve):

$$N = N \cdot n, \tag{6}$$

the sliding friction force, which, by Coulomb's law (Molchak et al., 1998), is taken as

$$T = -\mu \cdot N \cdot t, \tag{7}$$

and the weight and Archimedes buoyant force, whose resultant in the chosen non-inertial frame has the form

$$P = (m \cdot g - \rho_w \cdot g \cdot V) \cdot (-e_y), \tag{8}$$

where m is the mass of the point, g is gravitational acceleration, ρ_ω is water density, and V is the displaced volume (so that $m = \rho_s \cdot V$, ρ_s being the sapropel density).

According to Newton's second law (Molchak et al., 1998) written in the non-inertial frame, the relative acceleration of the material point is proportional to the vector sum of active forces, constraint reactions, and inertia forces, i.e.,

$$m \cdot a_{rel} = P + T + N + F_{tr} + F_{cor}. \tag{9}$$

We write vector equality (9) in projections onto the axes of the natural frame *(t, n)*. To this end, we take the scalar product of (9) first with *t* and then with *n*, using the relations

$$t \cdot t = 1, n \cdot n = 1, t \cdot n = 0, a_{rel} \cdot t = \ddot{s}, a_{rel} \cdot n = \frac{\dot{s}^2}{\rho}$$

$$a_{tr} \cdot t = a_{tr,t}, a_{tr} \cdot n = a_{tr,n}, a_{cor} \cdot t = a_{cor,t}, a_{cor} \cdot n = a_{cor,n}$$

$$P \cdot t = P_t, P \cdot n = P_n$$

In this way we obtain the equation of relative motion along the curve $s = s(\varphi)$:

$$m\ddot{s} = Pt - \mu N sgn(\dot{s}) - m a_{tr,t} - m a_{cor,t}. \tag{10}$$

where

$$N = P_n - m \cdot a_{tr,n} - m \cdot a_{cor,n} + m\frac{\dot{s}^2}{\rho}. \tag{11}$$

$$a_{tr,t} = -\omega^2 r \frac{r'}{\sqrt{(r')^2 + r^2}}, a_{tr,n} = +\omega^2 r \frac{r}{\sqrt{(r')^2 + r^2}}.$$

If the material point is placed on the curve with zero initial absolute velocity, then the initial conditions, given the adopted directions of φ and the frame's angular velocity ω, are

$$s(0) = s_0, s^{\cdot}(0) = 0. \tag{12}$$

Equation (10) must be solved under the non-separation condition $N \geq 0$, i.e., the material point does not detach from the curve surface.

The differential equation (10) is nonlinear with variable coefficients; therefore, numerical methods are used. Since (10) contains a discontinuous function $sgn(\dot{s})$ (from Coulomb friction), to ensure stability a fixed-step scheme is required. Hence, the fourth-order Runge-Kutta method is optimal.

Implementation of the problem in the MATLAB environment, taking into account the assumed and theoretically obtained parameters, confirmed the feasibility of the proposed working process of the extracting organ. However, achieving the desired transport of sapropel along the Archimedes spiral is possible when the cutter's rotation frequency is increased from the proposed 15 min^{-1} to 20 min^{-1}, while a stable operating regime is achieved at 25 min^{-1}, which is allowed by the proposed standards.

The solution of the mathematical model made it possible to obtain the following graphical dependencies: the angular position of the point on the cutter blade versus time (Fig. 2), the relative angular velocity with respect to the blade (Fig. 3), and the trajectory of the point in absolute coordinates (Fig. 4).

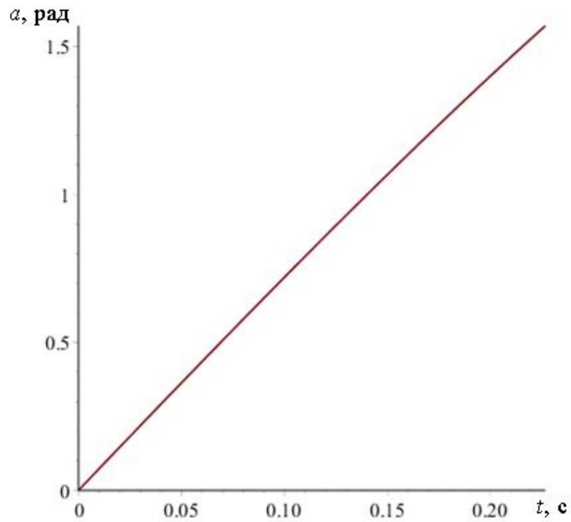

Figure 2 – Angular position of the point on the cutter blade as a function of time.

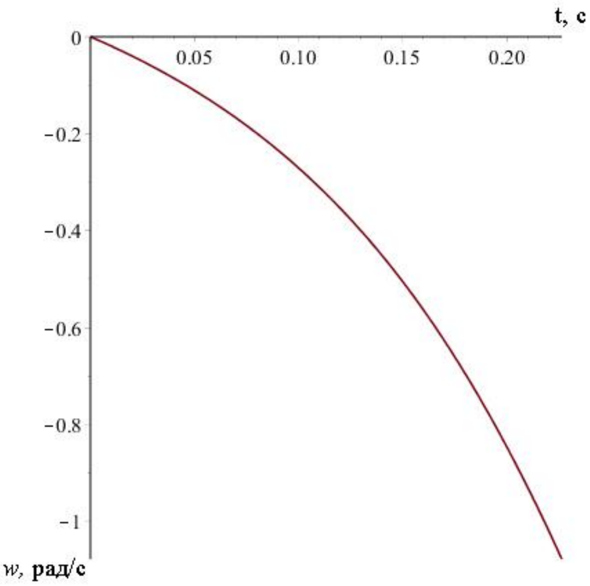

Figure 3 – Relative angular velocity of the point with respect to the cutter blade.

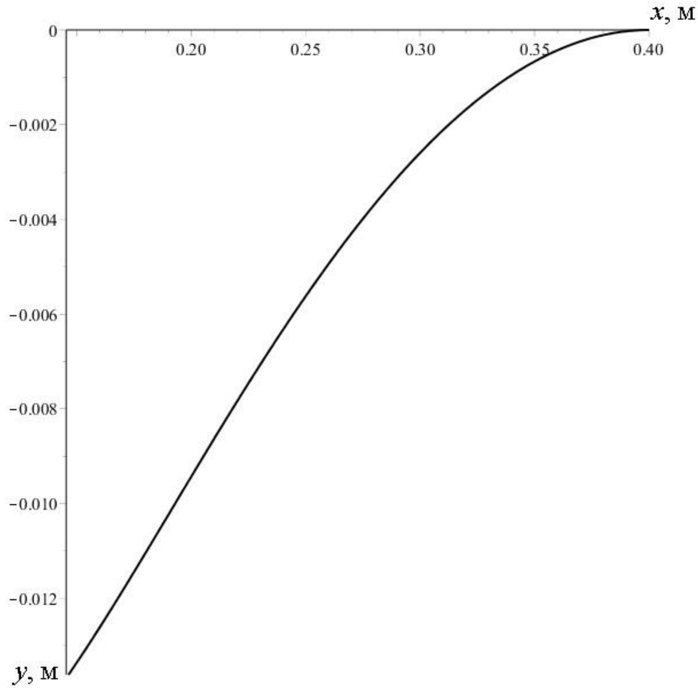

Figure 4 – Trajectory of the point in absolute coordinates.

To generalize the research results and transfer the obtained dependencies to other types of viscoplastic media, a **material similarity coefficient** k_m was introduced. It accounts for the physico-mechanical parameters of the processed material. The coefficient is defined as the ratio of density, moisture content, and rheological characteristics of the studied material to the corresponding parameters of sapropel:

$$K_m = \frac{\rho_m}{\rho_s} \cdot \frac{\mu_m}{\mu_s} \cdot \frac{W_m}{W_s} \tag{13}$$

where: ρ_m, ρ_s – density of the material and sapropel, kg/m³;

μ_m, μ_s – dynamic viscosity of the material and sapropel, Pa·s;

W_m, W_s – moisture content of the material and sapropel, %.

The obtained coefficient k_m makes it possible to **scale the kinematic and energy parameters** of the transportation process described by the mathematical model. For example, for **natural-moisture silt** ($\rho = 1300$ kg/m³, $\mu = 60$ Pa·s, $W = 75\%$), the coefficient $K_m \approx 1,12$. In contrast, for a **peat suspension** ($\rho = 1100$ kg/m³, $\mu = 45$ Pa·s, $W = 70\%$), $k_m \approx 0,89$. This indicates that transporting such materials in a spiral working body requires only minor adjustment of the cutter rotation speed (within ±10%) to ensure stable movement of the mass.

Thus, the **material similarity coefficient** can be used to determine the operating modes of machines employed for extraction, dewatering, or conveying of viscous organic materials, as well as in the modeling and design of other screw-type transport systems.

CONCLUSIONS

1. An analytical model of the motion of a material particle along the surface of an Archimedean spiral was developed, taking into account friction forces, buoyancy, and hydrostatic resistance in a water environment.
2. It was established that a stable mode of sapropel mass transportation is achieved at the rotational speed of the spiral working organ of 20–25 min^{-1}, which corresponds to the conditions of uniform material movement without segregation.
3. A material similarity coefficient K_m was proposed, which allows the mathematical model to be adapted to different viscoplastic media (such as silt, peat, technical pastes, etc.).

4. The model confirms the possibility of optimizing the structural parameters of the spiral cutter without the need for multiple large-scale field experiments, which significantly reduces the scope of full-scale testing.
5. The obtained results can be used for the design of energy-efficient screw-type transportation systems for natural organic masses with adjustable feed rates.

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