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THE MOTION OF A PARTICLE ON A WAVY SURFACE DURING ITS TRANSLATIONAL CIRCULAR OSCILLATIONS IN HORIZONTAL PLANES

Т.М. Воліна, С.Ф. Пилипака, В.М. Бабка. **Рух частинки по хвилястій поверхні під час її поступальних колових коливань у горизонтальних площинах.** Шорстка площина є універсальним конструктивним елементом багатьох машин і пристроїв для просіювання і сепарації частин технологічного матеріалу. Найбільш дослідженим є рух частинок по горизонтальній площині, яка здійснює коливальний прямолінійний або круговий рухи. Хвиляста поверхня із поперечним перерізом у вигляді синусоїди в ролі робочої поверхні суттєво змінюватиме траєкторії ковзання частинок. Відповідно зміниться і математичний опис такого руху. Ковзання частинки по площині буде частковим випадком ковзання по хвилястій поверхні, коли амплітуда синусоїди дорівнюватиме нулю. При коливаннях хвилястої поверхні, коли всі її точки описують кола, рух технологічного матеріалу суттєво змінюється. У статті досліджуються закономірності руху матеріальних частинок по такій поверхні під час її колових поступальних коливань в горизонтальних площинах. Складено диференціальні рівняння відносного переміщення частинки, які розв'язано чисельними методами. Побудовано траєкторії ковзання частинки по поверхні та графіки її реакції. Частковим випадком поверхні є площина, а траєкторією ковзання частинки є коло. Знайдено аналітичний вираз для визначення його радіуса. При колових коливаннях хвилястої лінійчатої поверхні з поперечним перерізом у вигляді синусоїди відносною траєкторією частинки після стабілізації руху може бути замкнена або періодична просторові криві. Для уникнення відриву частинки від поверхні потрібно задавати режим коливань, який враховує форму поверхні та кінематичні параметри коливань. При діаметрі кола, яке описують усі точки поверхні при її коливанні, рівному періоду синусоїди, траєкторією відносного руху частинки може бути періодична крива. У цьому випадку частинка рухається в напрямі, близькому до поперечного, долаючи впадини і гребні поверхні. У інших випадках траєкторією є замкнена просторова крива, горизонтальна проекція якої близька до кола. Знайдені аналітичні залежності дозволяють визначати вплив конструктивних та технологічних параметрів поверхні на траєкторію руху частинки по ній.
Ключові слова: частинка, хвиляста поверхня, колові коливання, диференціальні рівняння, кінематичні параметри

T. Volina, S. Pylypaka, V. Babka. **The motion of a particle on a wavy surface during its translational circular oscillations in horizontal planes.** The rough plane is a universal structural element of many machines and devices for sifting and separation of parts of technological material. The motion of particles on the horizontal plane, which performs oscillating rectilinear or circular motion, is the most studied. A wavy surface with a sinusoidal cross-sectional line as a working surface will significantly change the trajectories of their motion. The mathematical description of such a motion will change accordingly. The sliding of a particle in a plane will be a partial case of sliding on a wavy surface when the amplitude of the sinusoid is equal to zero. When the wavy surface oscillates and all its points describe circles, the motion of the technological material changes significantly. The regularities of the motion of material particles on such a surface during its circular translational oscillations in the horizontal planes are investigated in the article. Differential equations of relative particle displacement are compiled and solved by numerical methods. The trajectories of the particle sliding on the surface and the graphs of its reaction are constructed. A partial case of a surface is a plane, and the sliding trajectory of a particle is a circle. An analytical expression to determine its radius is found. During circular oscillations of a wavy linear surface with a cross section in the form of a sinusoid relative trajectory of a particle after stabilization of the motion can be closed or periodic spatial curves. To avoid the breakaway of the particle from the surface, the oscillation mode should be set, which takes into account the shape of the surface and the kinematic parameters of oscillations. With the diameter of the circle, which is described by all points of the surface during its oscillation, is equal to the period of the sinusoid, the trajectory of the relative motion of the particle can be a periodic curve. In this case, the particle moves in a direction close to the transverse, overcoming depressions and ridges. In other cases, the trajectory is a closed spatial curve, the horizontal projection of which is close to a circle. The found analytical dependencies allow determining the influence of structural and technological parameters of the surface on the trajectory of the particle.
Keywords: particle, wavy surface, circular vibrations, differential equations, kinematic parameters

1. Introduction

The rough plane is a universal structural element of many machines and devices for sifting and separation of parts of technological material. The most studied is the motion of particles in the horizontal plane, which performs oscillating rectilinear or circular motion [1]. A wavy surface with a sinusoidal cross-section as a working surface will significantly change the sliding trajectories of the par-

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ticles. The mathematical description of such a movement will change accordingly. The sliding of a particle on a plane will be a partial case of sliding on a wavy surface when the amplitude of the sinusoid is equal to zero. At oscillations of a wavy surface when all its points describe circles, the movement of technological material changes essentially.

2. Analysis of recent publications and problem statement

The motion of material particles on surfaces is considered in scientific articles in the context of their nature. These can be mechanical particles, gas or liquid particles, particles in a stream, and so on. Of course, the motion of an individual particle cannot be identified with the motion of a body or with the motion of a process material consisting of individual particles, and in the study of the motion of which the forces of inertia arising during body rotation must be taken into account. In some cases, at low angular velocities, these forces can be ignored. For example, as in the study of the motion of a particle on the outer surface of a cylinder that performs translational oscillations in horizontal planes [2]. However, based on the motion of an individual particle, it is possible to identify dependencies that can be applied to the body or to the technological material or help to determine the direction of further research. Thus, scientists have considered the movement of material particles on moving spiral working bodies [3]; on the helical surface [4]; on the gravitational descent formed by the surface of the oblique closed helicoid [5]; on a spherical segment that rotates around a vertical axis [6]; moving the particle in the inactive zone between the hinged screw sections of the flexible screw conveyor [7]. Therefore, to study the motion of a particle depending on the structural parameters of the surface, it is necessary to have analytical dependences describing such motion.

3. The purpose and objectives of the study

The aim of the article is to study the patterns of motion of material particles on a wavy surface, which performs circular translational oscillations in horizontal planes. The objectives of the study are to identify the analytical dependences of such motion and their analysis, which will determine the influence of structural and technological parameters of the surface on the trajectory of the particle. The wavy surface is a cylindrical surface with a horizontal arrangement of rectilinear generators and a cross section in the form of a sinusoid.

4. Presentation of the main material

Parametric equations of a cylindrical surface, in which the cross section is a sinusoid, and rectilinear generating parallel axes *OX*, are written:

$$X = u; \quad Y = v; \quad Z = c\sin av, \tag{1}$$

where c – amplitude, and a – is frequency (constant values); u, v – independent variable surfaces, where u – is the length of the rectilinear generator, v – is the distance along the OY axis.

The cylindrical wavy surface performs translational oscillations in such a way that all its points describe circles. Fig. 1 shows the trajectories of the four points of the surface. The absolute motion of the particle will be considered in relation to the fixed coordinate system *OXYZ*.

If the surface is tied to a moving coordinate system, then when it oscillates, the axes of the moving and fixed systems will always be parallel. This means that the absolute trajectory of the particle can be written as the sum of the transfer motion of the surface, the points of which describe the circles and the relative motion of the point on the wavy surface:

$$x = x_e + x_r;$$
$$y = y_e + y_r; \tag{2}$$
$$z = z_e + z_r,$$

where $x_e = x_e(t)$; $y_e = y_e(t)$; $z_e = z_e(t)$ – the trajectory of the figurative motion of the surface as a

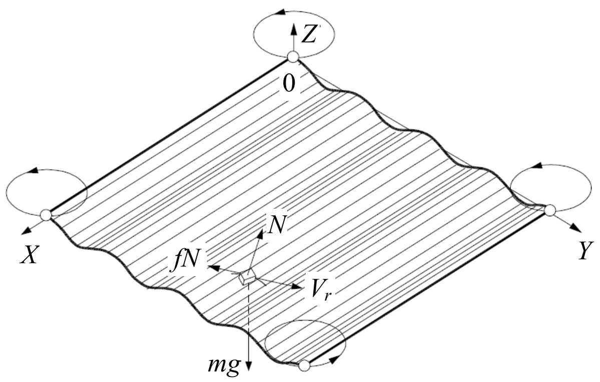

Fig. 1. Scheme of circular oscillations of a wavy surface and forces applied to a particle

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function of time t; $x_r = x_r(t)$; $y_r = y_r(t)$; $z_r = z_r(t)$ – the trajectory of the relative motion of the particle on the surface as a function of time t.

Let r – radius of the circles along which the points of the cylinder move. Then the figurative motion of the points of the wavy surface will be described by the equations:

$$x_e = r\cos\omega t; \quad y_e = r\sin\omega t; \quad z_e = 0, \tag{3}$$

where ω – angular velocity of rotation of surface points in circles.

The point will slide along a certain trajectory on the surface. The trajectory equation can be obtained by relating the independent variables v and u of the surface (1). This connection is written in time t, ie the coordinates of the particle on the wavy surface will be functions of time: $v = v(t)$ and $u = u(t)$. In this case, the relative motion of the particle is written by the equations:

$$x_r = u; \quad y_r = v; \quad z_r = c\sin av. \tag{4}$$

Summing the portable (3) and relative (4) motions by formula (2), we obtain the equation of the absolute trajectory of the particle:

$$x = u + r\cos\omega t; \quad y = v + r\sin\omega t; \quad z = c\sin av. \tag{5}$$

The dependences $v = v(t)$ and $u = u(t)$, which describe the trajectory of relative motion (sliding of a particle on a wavy surface), are unknown functions to be found. After differentiation of equations (5) by time t we find the projections of the absolute velocity of the particle:

$$x' = u' - r\omega\sin\omega t; \quad y' = v' + r\omega\cos\omega t; \quad z' = acv'\cos av. \tag{6}$$

By differentiating expressions (6) we obtain projections of absolute acceleration:

$$x'' = u'' - r\omega^2\cos\omega t; \quad y'' = v'' - r\omega^2\sin\omega t; \quad z'' = ac(v''\cos av - av'^2\sin av).$$

We compose the equation of motion in the form $m\overline{w} = \overline{F}$, where m is the mass of the particle, $\overline{w}$ – absolute acceleration vector, $\overline{F}$ – the resulting vector of forces applied to the particle. These forces are (Fig. 1): the force of gravity mg ($g = 9.81$ m/sec^2), the reaction N of the surface and the friction force fN when the particle slides on the surface (f is the coefficient of friction). All forces must be projected on the axis of the $OXYZ$ coordinate system.

The force of gravity is directed downwards, so its projections will be written:

$$\{0; \quad 0; \quad -mg\}.$$

The reaction N of the surface is directed along the normal to it and is determined from the vector product of two vectors tangent to the coordinate lines of the surface. The projections of these vectors are partial derivatives of equations (1):

$$\frac{\partial X}{\partial v} = 0; \quad \frac{\partial Y}{\partial v} = 1; \quad \frac{\partial Z}{\partial v} = ac\cos av; \quad \frac{\partial X}{\partial u} = 1; \quad \frac{\partial Y}{\partial u} = 0; \quad \frac{\partial Z}{\partial u} = 0. \tag{7}$$

After multiplication of vectors (7) and reduction of the received vector to unit, projection of a vector of a normal to a surface will be written:

$$\left\{0; \quad -\frac{ac\cos av}{\sqrt{1 + a^2c^2\cos^2 av}}; \quad \frac{1}{\sqrt{1 + a^2c^2\cos^2 av}}\right\}.$$

The force of friction is directed along the tangent to the trajectory of the relative motion of the particle in the opposite direction to the vector of the particle sliding speed. The direction of the vector is determined by the first derivatives of equations (4):

$$x_r' = u'; \quad y_r' = v'; \quad z_r' = acv'\cos av. \tag{8}$$

The geometric sum of the components (8) will give the value of the sliding speed of the particle on the wavy surface in relative motion:

$$V_r = \sqrt{x_r'^2 + y_r'^2 + z_r'^2} = \sqrt{u'^2 + v'^2(1 + a^2c^2\cos^2 av)}. \tag{9}$$

The unit vector of the tangent in the projections on the axis of the system *OXYZ* is obtained by dividing the projections (8) by the value of the vector (9):

$$\left\{\frac{u'}{V_r};\ \ \frac{v'}{V_r};\ \ \frac{acv'\cos av}{V_r}\right\}. \tag{10}$$

We describe the vector equation $m\overline{w} = \overline{F}$ in projections on the axis of the coordinate system, taking into account that the friction force fN is directed along the unit vector (10) in the opposite direction:

$$\begin{gathered} m(u'' - r\omega^2\cos\omega t) = -fN\frac{u'}{V_r}; \\ m(v'' - r\omega^2\sin\omega t) = -\frac{Nac\cos v}{\sqrt{1 + a^2c^2\cos^2 av}} - fN\frac{v'}{V_r}; \\ mac(v''\cos av - av'^2\sin av) = -mg + \frac{N}{\sqrt{1 + a^2c^2\cos^2 av}} - fN\frac{acv'\cos av}{V_r}. \end{gathered} \tag{11}$$

System (11) includes three unknown functions: $N = N(t)$, $u = u(t)$ and $v = v(t)$. Solving it with respect to N, u “and v”, we obtain the following expressions:

$$\begin{gathered} v'' = \frac{1}{A^2}[r\omega^2\sin\omega t + ac(a^2cv'^2\sin av - g)\cos av] - \frac{fv'}{AV}B; \\ u'' = r\omega^2\cos\omega t - \frac{fv'}{AV}B; \quad N = \frac{m}{A}B, \end{gathered} \tag{12}$$

where $A = \sqrt{1 + a^2c^2\cos^2 av}$; $\quad B = [g + ac(r\omega^2\cos av\sin\omega t - av'^2\sin av)]$.

5. Research results

System (12) cannot be integrated in analytical form. It must be solved by numerical methods. The found dependences $v = v(t)$ and $u = u(t)$ must be substituted into equation (4) in order to obtain the relative trajectory of the particle on the wavy surface, ie the sliding trajectory. If the amplitude $c = 0$, then the parametric equations of the surface (1) are converted into the equation of the horizontal plane. In this case, the system (12) is greatly simplified:

$$\begin{gathered} v'' = r\omega^2\sin\omega t - fg\frac{v'}{\sqrt{u'^2 + v'^2}}; \\ u'' = r\omega^2\cos\omega t - fg\frac{u'}{\sqrt{u'^2 + v'^2}}; \\ N = mg. \end{gathered} \tag{13}$$

In Fig. 2 numerical methods constructed the trajectory of the particle sliding along the plane with the following parameters: $r = 0.05$ m, $\omega = 10$ s^{-1}, $f = 0.3$. After the transition process, the trajectory of the particle is a circle whose radius is smaller than the circle described by all points of the plane.

Figure 3 shows a graph of the change in the speed V_r of sliding for 3 s. It shows that after the transition process, when the trajectory of the relative motion of the particle becomes a circle, the sliding speed becomes constant. We will use this fact to find an analytical description of the sliding of a particle after stabilization of its motion. When $\sqrt{u'^2 + v'^2} = V_r = \text{const}$, system (13) splits into two independent differential equations:

$$v'' = r\omega^2\sin\omega t - fg\frac{v'}{V_r};\ u'' = r\omega^2\cos\omega t - fg\frac{u'}{V_r}.$$

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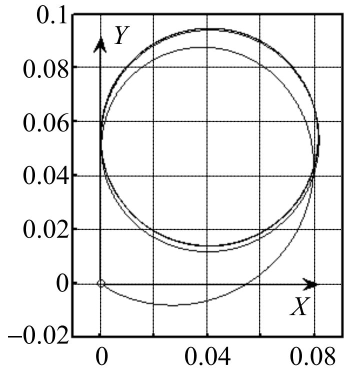

Fig. 2. The sliding trajectory of the particles

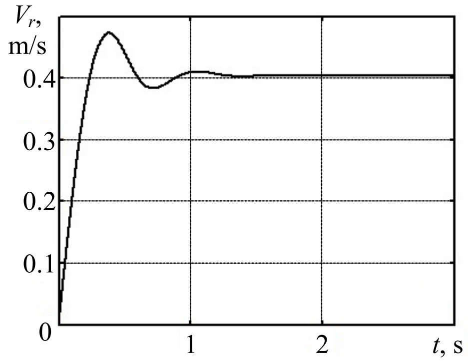

Fig. 3. Graph of particle velocity change

Their partial solutions, when the integration constants are zero, will be written:

$$v = -\frac{rV_r\omega}{f^2g^2 + V_r^2\omega^2}(fg\cos\omega t + V_r\omega\sin\omega t);$$
$$u = \frac{rV_r\omega}{f^2g^2 + V_r^2\omega^2}(fg\sin\omega t - V_r\omega\cos\omega t). \quad (14)$$

Find the expression for the constant V_r through the given parameters of the oscillatory motion. Differentiate equation (14) and find:

$$V_r = \sqrt{u'^2 + v'^2} = \frac{rV_r\omega^2}{\sqrt{f^2g^2 + V_r^2\omega^2}}. \quad (15)$$

Solving (15) with respect to V_r, we find:

$$V_r = \frac{\sqrt{r^2\omega^4 - f^2g^2}}{\omega}. \quad (16)$$

Substitute (16) into (14) and finally find the parametric equations that describe the trajectory of the particle sliding along the plane in relative motion after its stabilization:

$$v = -r\sin\omega t + \frac{fg}{r\omega^4}(fg\sin\omega t - \sqrt{r^2\omega^4 - f^2g^2}\cos\omega t);$$
$$u = -r\cos\omega t + \frac{fg}{r\omega^4}(fg\cos\omega t + \sqrt{r^2\omega^4 - f^2g^2}\sin\omega t). \quad (17)$$

If the plane is absolutely smooth, ie $f = 0$, then the equations of relative motion (17) have the opposite sign of the equations of figurative motion (3), as a result of which the particle in absolute motion according to equations (5) remains stationary. From equations (17) we find the radius r_r of the circle, which describes the particle, sliding along the plane after stabilization of motion:

$$r_r = \sqrt{u^2 + v^2} = r\sqrt{1 - \left(\frac{fg}{r\omega^2}\right)^2}.$$

The radius r_r approaches the radius r as the coefficient f of friction decreases or as the angular velocity ω of the plane oscillations increases.

6. Discussion of results

Construct the relative trajectories of the particle on a wavy surface. It should be noted that the shape of the surface must be limited in some way due to the parameters of its cross section. A sinusoid with constants $c = 0.005$ (amplitude) and $a = 62.8$ (period $T = 0.1$) was taken, ie the ratio of amplitude to period is 1:20. At lower ratios, the particle separates from the surface. This ratio is not fixed. It depends on the radius r of the circles along which the surface oscillates, the angular velocity ω, the coefficient of friction f.

The first case. The diameter of the circles of the figurative motion of the surface is equal to the period: $2r = T$. This case is typical because the trajectory of the particle sliding on the surface is not a closed line (Fig. 4). The trajectory of sliding is a periodic spatial curve, while the curvilinear sliding of the particle propagates in a direction close to the direction of the axis OY, and the particle in its motion overcomes the depressions and ridges of the surface. The direction of propagation of such motion can occur both in the direction of the OY axis and in the opposite direction. The behavior of the particle depends on the point of impact on the surface.

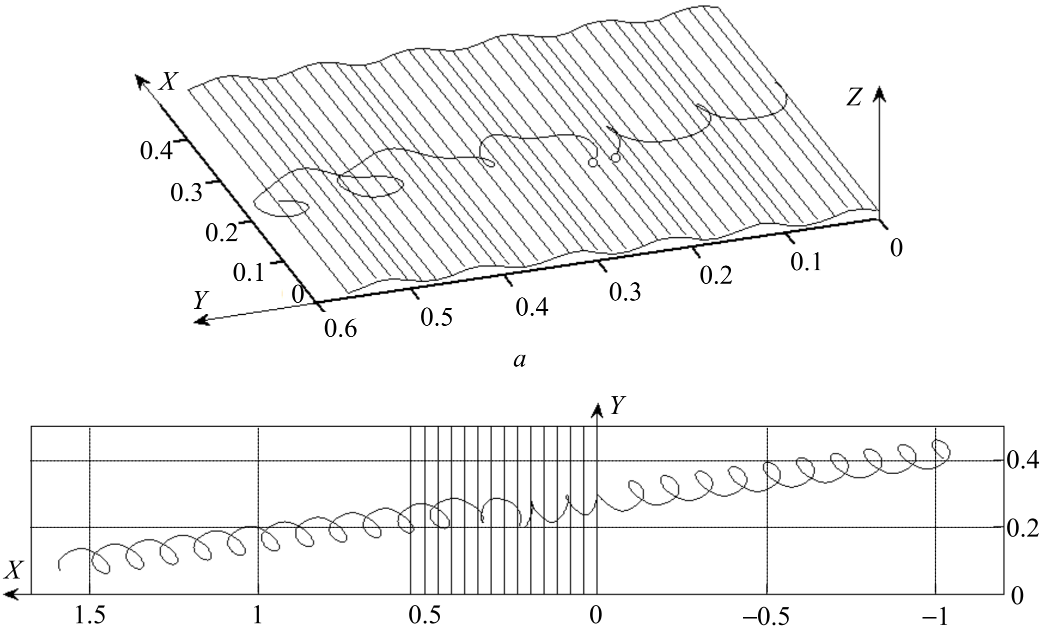

Fig. 4. The trajectory of the relative motion of the particle on the wavy surface at $r = 0.05$ m, $\omega = 10$ s^{-1}, $f = 0.3$, $c = 0.005$, $a = 62.8$: the trajectory of the particle in a limited area of the surface in axonometric (*a*); the trajectory of the particle on the horizontal projection for 8 s (*b*)

In Fig. 4, *a*, the trajectories of the relative motion of the particle are constructed on a limited section of the surface where the transition process takes place, indicating the point of impact on the surface. Fig. 4, *b*, shows a horizontal projection of the trajectories of the relative motion of a particle that has been moving for 8 s.

When a particle slides on a wavy surface, its reaction N changes in contrast to the plane, where $N = mg$. In Fig. 5 is a graph of the change in surface reaction for a particle with mass $m = 0.01$ kg. It is built for one of the trajectories shown in Fig. 4, *b*, and is characteristic of another trajectory.

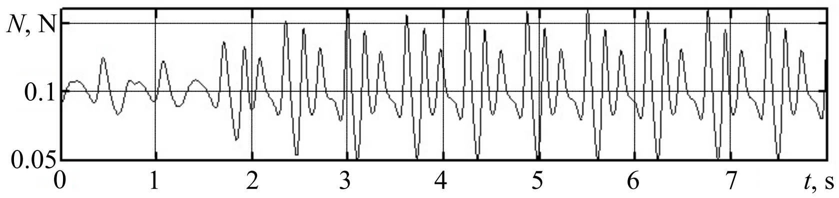

Fig. 5. Graph of the change in the reaction of the surface to a particle that slides on a wavy surface

As the angular velocity of oscillations ω increases, the nature of the propagation of oscillations does not change, but at certain points in time the reaction of the surface becomes negative, ie the direc-

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tion of its vector changes to the opposite. In this case, the trajectory of the particle would be real if it moved between two parallel surfaces. Since we have only one surface, then at the moment when the reaction becomes equal to zero, there is a separation of the particle from the surface, ie its further trajectory becomes unknown. Given this, we consider only those cases of movement when the reaction has a positive sign.

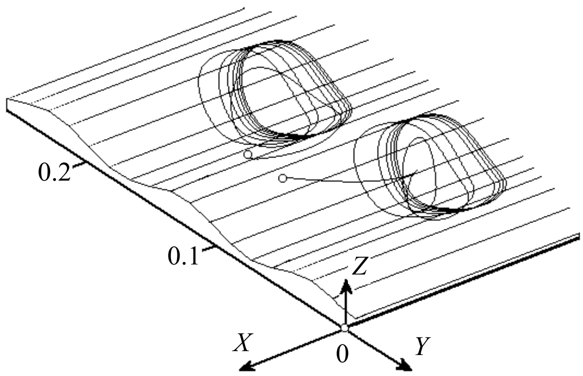

Fig. 6. The trajectory of the relative motion of a particle on a wavy surface at $r = 0.04$ m, $\omega = 10\ s^{-1}$, $f = 0.3$, $c = 0.005$, $a = 62.8$

The second case. The diameter of the circles of the portable motion of the surface is less than the period: $2r < T$. In this case, after the transition period, the sliding trajectory of the particle becomes closed. In Figure 6 constructs the trajectories of the relative motion of the particle on the wavy surface for all previous parameters, including the points of impact of the particle on the surface, with a change of only one parameter: $r = 0.04$ m.

The third case. The diameter of the circles of the portable motion of the surface is larger than the period: $2r > T$. In this case, the transition period can last quite a long time, as shown in Fig. 7 (at $\omega = 10\ s^{-1}$), or rather move to a closed trajectory with increasing angular velocity ω (at $\omega = 15\ s^{-1}$).

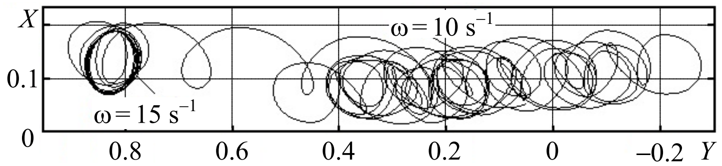

Fig. 7. Horizontal projection of trajectories of relative motion of a particle on a wavy surface at $r = 0.06$ m, $\omega = 10\ s^{-1}$, $f = 0.3$, $c = 0.005$, $a = 62.8$

With a further increase in the radius r, the particle moves along a closed curve after the transition period, and this closed curve increases in size according to the radius r of circular oscillations. Figure 8 shows the trajectory of the particle as the radius r of the oscillations increases to 0.07 m. If we reduce the amplitude c of the sinusoid, the wavy surface will approach the plane, and the closed slip curve will approach the circle.

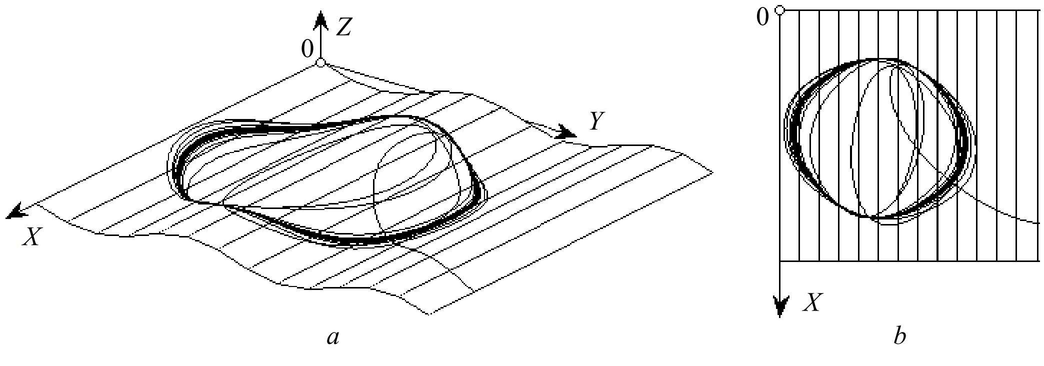

Fig. 8. The trajectory of the relative motion of a particle on a wavy surface at $r = 0.07$ m, $\omega = 10\ s^{-1}$, $f = 0.3$, $c = 0.005$, $a = 62.8$: axonometric image (*a*); horizontal projection (*b*)

The considered cases quite fully reflect possible trajectories of relative motion of a particle on a wavy surface at its circular oscillations. The article does not show the influence of the coefficient of friction f on the trajectory of the particle, but its value does not make significant changes in the nature of the sliding curves of the particle and is limited to the cases considered.

7. Conclusions

At circular oscillations of a wavy linear surface with a cross section in the form of a sinusoid relative trajectory of a particle after stabilization of the movement can be closed or periodic spatial curves. To avoid separation of the particle from the surface, you need to set the oscillation mode, which takes into account the shape of the surface and the kinematic parameters of the oscillations. When the diameter of the circle, which describes all points of the surface during its oscillation, equal to the period of the sinusoid, the trajectory of the relative motion of the particle can be a periodic curve. In this case, the particle moves in a direction close to the transverse, overcoming depressions and ridges. In other cases, the sliding trajectory is a closed spatial curve, the horizontal projection of which is close to a circle.

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