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CONSTRUCTING A MODEL OF THE AXIS FORM IN A S-SHAPED RISER OF A CULTIVATOR PAW

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When cultivating the soil, a force of resistance to the movement of cultivator paw acts on it. It has a variable value and causes a moment of force applied to the riser of the paw. Under the action of the moment, the elastic axis of the riser changes its shape. This affects the position of the paw in the soil. The form of an S-shaped riser whose elastic axis consists of two circle arcs has been considered in this study. During cultivator operation, one part of the riser bends, increasing the curvature of the elastic axis, and the other, on the contrary, unbends, that is, its curvature decreases.

The modeling of the shape of the elastic axis of the paw riser is based on the theory of resistance of materials, according to which the curvature of the elastic axis of the cantilevered band is directly proportional to the applied moment and inversely proportional to its stiffness. If the shape of the cross-section of the riser along its entire length is unchanged and the properties of the metal are also the same, then the stiffness is constant. In the case of small deflections of the band, the linear theory of bending is used, but the deflections in the riser are significant, so the nonlinear theory has been used for this case. At the same time, it is taken into account that the elastic axis of the riser already has an initial curvature, the sign of which changes after passing through the point of connection of the component arcs.

To model the shape of the elastic axis of the S-shaped paw riser, the deformation of the arcs of the circles that form this paw was calculated separately. Numerical integration methods were used to find the shape of the deformed elastic axes of both parts of the riser. They were connected into a whole and a deformed elastic axis of the S-shaped riser was obtained. Two variants of the riser with different lengths of their elastic axis, but the same height and the same angle of entry into the soil, were considered. The combination of the component arcs of the riser shows that, under the action of the same force, the deviation from the specified movement depth for one riser is 2 cm, and for the other – 4 cm

Keywords: tillage, working body, elastic axis, circle arc, moment of force

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1. Introduction

Resistance forces act on the cultivator paw as a result of its cutting the roots of weeds and loosening the soil. These forces of variable magnitude are transmitted to the riser. There are different forms of risers of the cultivator paw. They accept pulsating dynamic loads, which are smoothed in a certain way. This leads to a periodic change in the shape of their elastic axis. The spring axis is deformed under the action of the applied moment and can take its original shape in its absence, i.e., the springing of the riser occurs. As a result of such springing, the cultivator paw partially changes its position, which affects the direction of the blade entering the soil and the deviation of its course from the given depth. Based on this, it is relevant to study the shape of an elastic curvilinear rod of double curvature under the action of the applied force, which could be used in the design of the riser of the cultivator paw.

2. Literature review and problem statement

A mechanical model of an elastic rod in a viscoelastic medium, provided it is fixed in the base, is proposed in [1]. The rod is subjected to an axial force and a locally distributed horizontal load. That study provides a sound theoretical basis for understanding the displacement of elastic rods in viscoelastic media. However, the research results were not further developed in the modernization of the shape of such a rod [1].

The bending of a band with a given initial curvature into a spiral shape is considered in work [2]. Similar to [1], the band is fixed at the lower point, and a certain force is applied to its upper end. The authors emphasize that with an increase in the applied force and the length of the band, the amount of deflection will increase, and the band may acquire a spiral shape. However, study [2] is limited only to this form of the band.

Work [3] reports the study on the processes of wear of the blades of cultivator paws with different types of strengthening and their influence on the change in traction resistance of the tillage unit. However, the authors did not take into account the possible variability of the forms of the working bodies of tillage implements. This may be due to the costly part of this kind of research.

Study [4] analyzed the power characteristics of the working bodies and the quality of the soil at the stage of designing tillage machines. The results make it possible to optimize the structural and technological parameters of their working bodies. But the authors did not pay attention to the issue of manufacturing working bodies of various configurations. The reason for this may be the purely theoretical nature of the research conducted by the authors.

Work [5] proposed the design of working bodies of various forms using computer modeling of their interaction with the soil. This makes it possible to immediately investigate the feasibility of the proposed solutions. In study [6], a mathematical model of the operation process of the tillage unit for Band-till technology in the technological system "Soil-aggregate-energy device" was developed and substantiated, and its intra-system dependences and connections were analyzed. However, similarly to [4], in these works, the issues of manufacturing working bodies of appropriate forms remain unsolved, which is also caused by the theoretical nature of these studies.

In study [7], this drawback is eliminated. The authors substantiated the geometric model and parameters of the surface of the cultivator paw equipped with elements of local strengthening. The method of designing the surface of the cultivator paw has been devised, including the construction of its sweep, which is a prerequisite for the manufacture of the proposed structure. However, the variability of the forms of working bodies was neglected because of high cost of research.

When cultivating the soil, a force of resistance to its movement acts on the cultivator paw. It has a variable value and causes a moment of force applied to the riser of the paw. Under the action of the moment, the elastic axis of the riser changes its shape. This affects the position of the paw in the soil. Oscillatory movements of the working body in the longitudinal-vertical plane were studied in [8]. The structural and kinematic parameters of the system under study were determined by computer simulation. The authors claim that the given method of mathematical modeling of the oscillating process can be used in the study of any machines that attach in front of the aggregating tractor. The study is limited to the working body of the machine for harvesting root crops. But the questions regarding the application of the proposed methodology to the design of other working bodies remained unresolved.

In works [9, 10] it is stated that it is possible to increase the reliability of working bodies of machines under ordinary operating conditions due to the application of a coating, without significantly changing its geometric parameters. In [11, 12], the attention is focused on cultivator paws. However, this issue can be partially resolved already at the stage of designing the working body. After all, the solution to such a complex problem cannot be based on the use of one group of methods but requires a comprehensive approach using the spectrum of available groups of methods.

Study [13] reports the results of theoretical studies on the dynamic model of the process of deformation of an elastic rack of a disk tool of arbitrary shape. The authors built the system of differential equations in general form and the corresponding program code in the Mathematica software package. This allows one to determine the stress, relative and absolute deformations at each point of the elastic support of the disk drive. However, the authors limited the shape of the elastic support of the disk drive in the form of an Archimedean spiral. The reason for this may be objective difficulties associated with the complexity of designing the shape of the working body in the form of other curves.

Based on the above, in available studies, the axis of the riser of the cultivator paw has a regular character of curvature change and is described by one dependence. The shape of the axis of the S-shaped riser is proposed, which consists of two arcs of circles of different curvature, and these arcs have a different sign of curvature. This leads to the fact that during the operation of the riser, it is deformed in such a way that the curvature of one part decreases, and the other increases.

3. The aim and objectives of the study

The purpose of our study is the formation of the S-shaped riser of the cultivator paw, taking into account its elastic bending under the action of the resistance force of the soil environment. This will make it possible to design the shape of the elastic axis of the riser, provided that during operation the deviation of its working end in height will be within the specified limits.

To achieve the goal, the following tasks were set:

– to devise an analytical description of the bending of the lower part of the elastic axis of the riser in the form of an arc of a circle, as a result of which the curvature of the axis decreases;

– to devise an analytical description of the bending of the upper part of the elastic axis of the riser in the form of an arc of a circle, as a result of which the curvature of the axis increases;

– to combine two deformed arcs into an *S*-shaped elastic axis for comparison with the initial position.

4. The study materials and methods

The object of our study is the shape of the riser of the cultivator paw of double curvature. The hypothesis of the research assumed conventionally dividing it into two parts, studying the deformation of each part and combining the two deformed parts into a single whole.

Research materials are based on the theory of nonlinear band bending, which is an integral part of the general theory of resistance of materials. When the elastic axis of the band is deformed, its curvature changes while the length of the arc of this axis does not change. An example of this can be the cantilevered band 1, which in its free state has a curvilinear shape (Fig. 1).

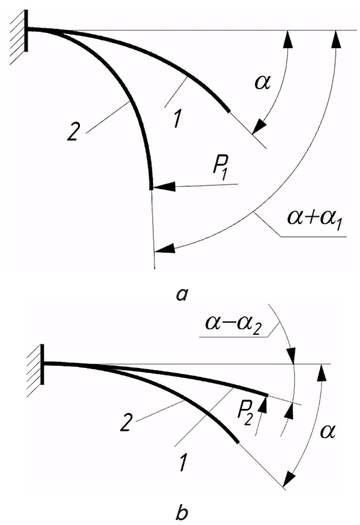

Fig. 1. Elastic axis of the band in the free state – 1 and after the applied force *P* – 2: *a* – the applied force *P* increases the curvature of the elastic axis; *b* – the applied force *P* reduces the curvature of the elastic axis

Depending on the direction of action of the force *P*, which is termed following because it remains perpendicular to the end of the axis during its deformation, the curvature of the axis can increase or decrease. The curvature of the axis in the free state can be estimated by the angle α, which either increases to $\alpha+\alpha_1$ (Fig. 1, *a*) or decreases to $\alpha-\alpha_2$ (Fig. 1, *b*) during its deformation. However, the value of the angle must be related to the length *s* of the elastic axis. The limit of this relation is the curvature *k* of the curve at the current point, i.e., $d\alpha/ds=k$. The shape of the curve depends on the regularity of the change of the angle α along the arc of the curve $\alpha=\alpha(s)$. If this dependence is linear, then the curvature *k* is a constant value, and the curve is an arc of a circle.

For the first case (Fig. 1, *a*), the curvature *k* of the elastic axis after deformation can be written as follows:

$$k(s)=\frac{d}{ds}\big(\alpha(s)+\alpha_1(s)\big)=k_0(s)+k_1(s), \quad (1)$$

where $k_0(s)$ is the curvature of the elastic axis in the free state, that is, before deformation; $k_1(s)$ is the additional curvature of the elastic axis acquired as a result of the action of the moment M_1 from the applied force P_1.

Accordingly, for the second case (Fig. 1, *b*), it is possible to write: $k=k_0-k_2$. The additional curvature $k_1(s)$ according to the theory of resistance of materials is determined from the expression:

$$k_1(s)=\frac{M_1(s)}{EI}, \quad (2)$$

where $M_1(s)$ is the applied moment M_1 to the curved band as a function of the arc length *s* of its elastic axis; *EI* is the stiffness of the band. It is the product of the moment of inertia *I* of the cross section of the band by the Young's modulus *E*.

The moment of force $M_1(s)$ is the product of force P_1 by the arc length *s* from the point of applied force P_1 to the current point of the elastic axis: $M_1=P_1s$. Taking this into account, substituting (2) into (1) gives the result:

$$k(s)=k_0(s)+\frac{P_1s}{EI},$$

or

$$\frac{d\alpha}{ds}=k_0+\frac{P_1s}{EI}. \quad (3)$$

For another case (Fig. 1, *b*), when the force P_2 "straightens" the elastic axis, equation (3) takes the form:

$$\frac{d\alpha}{ds}=k_0-\frac{P_2s}{EI}. \quad (4)$$

Equations (3) and (4) are the so-called natural equations of the elastic axis of the band after its deformation from the initial curvature k_0 in the free state to its increase or decrease. Differential geometry of curved lines is used to construct the axis of the band according to these equations. The transition to parametric equations is based on the well-known integrals:

$$x=\int\cos\alpha(s)\mathrm{d}s; \quad (5)$$

$$y=\int\sin\alpha(s)\mathrm{d}s.$$

Equations (5) require numerical methods of integration since the parametric equations of the deformed axis do not exist in their final form.

The hypothesis of the research is to gradually find the shape of the elastic axis of the riser when it is bent: first for the lower part, which is in contact with the soil, and then for the upper part. The border of these parts is the point at which the curvature of the axis changes its sign to the opposite. The assumption is the homogeneity of the metal along the length of the riser. The simplification is that the elastic axes of both parts of the riser are arcs of circles.

5. Results of modeling the shape of an elastic axis of the S-shaped riser of the cultivator paw

5. 1. Analytical description of the bending of the elastic axis of the lower part of the riser

The S-shaped riser of the cultivator foot may have different shapes. The main property of the riser is that it can be conventionally divided into two parts curved in opposite directions. Fig. 2 shows the attachment of the riser with one of its ends to the frame of the cultivator, and the second free end is intended for attachment of the paw. Under the action of the soil reaction force during cultivator operation, the riser undergoes pulsating loads, as a result of which it changes the shape of its elastic axis.

Fig. 2. S-shaped paw riser on the frame of the cultivator

Another riser with some dimensions (Fig. 3) is given in the advertisement by the company "Technovik" [14].

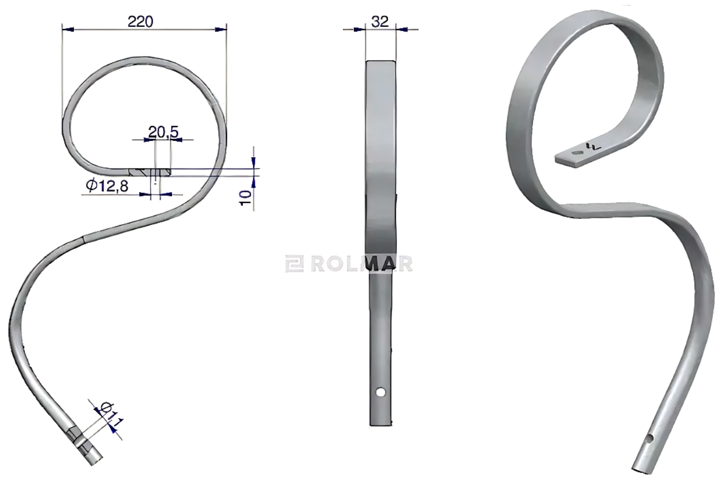

Fig. 3. Projections and visual representation of an S-shaped riser with some dimensions

First, it is advisable to consider the deformation of the elastic axis of the lower part of the riser, that is, the arc *AB* (Fig. 4). It is assumed that it is cantilever fixed at point *B* and under the action of soil resistance forces it expands, that is, its curvature decreases. In this case, you need to use equation (4). The stiffness *EI* can be determined based on the cross-sectional shape of the riser and its material, which is spring steel. According to Fig. 3, the upper part of the riser (arc *BC*) has a rectangular section of 0.01×0.032 m. Young's modulus of spring steel is $E=2.2\cdot10^{11}$ N/m^2. The moment of inertia of a rectangular cross-section is determined by the formula $I=a^3\cdot b/12$, where a and b are the sides of the rectangle, and in our case the smaller side is $a=0.01$ m. The result of the multiplication is as follows: $EI=586.67$ N·m^2. The lower part of the riser (arc *AB*) has a different cross-sectional shape, which obviously increases rigidity. Our research assumes that the stiffness is the same for both parts of the riser. Integrating expression (4) will give the result:

$$\alpha = k_0 s - \frac{Ps^2}{2EI}. \tag{6}$$

Let the resistance of the soil at a certain moment in time be $P=500$ N. Other data ($k_0=1/r_1=$ $=1/0.18=5.556$, $s=0.415$) are taken for the elastic axis of the first option (Fig. 4, *a*). Substitution of these data in formula (6) gives the result: $\alpha=2.3-0.073=2.227$ rad. An angle of 2.3 rad or 132° is formed between the tangents to the curve *AB* at the extreme points *A* and *B*, and the elastic axis is stretched by an angle of 0.073 rad or 4.2° under the action of the applied force $P=500$ N at point *A*.

To construct the elastic axis of the lower part of the riser (arc *AB*) after deformation, numerical integration of equations (5) is used, into which expression (6) is substituted. The result of integration is shown in Fig. 5, *a* (curve 2).

Similarly, the elastic axis of the lower part of the riser is constructed for its second variant (Fig. 4, *b*).

Judging from both images of the risers (Fig. 2, 3), the elastic axis of their upper part is similar to the arc of a circle, and the lower one is to the part of a parabola. To simplify calculations in the paper, both parts are replaced by arcs of circles. This does not narrow the general approach and can be applied to the arcs of other curves.

To apply the formulas given in chapter 4, the elastic axis of the S-shaped riser must be set with approximate dimensions corresponding to Fig. 3. At the same time, there may be different options. Fig. 4 shows two possible options with some common parameters. Parts 2 of the riser of both variants are arcs of circles of the same radius, and parts 1 – of different radii. The height $H=0.5$ m and the angle of entry into the soil $\beta=45°$ are also the same. Point *B* is the border between arcs 1 and 2, which are connected to each other according to the first order of smoothness, that is, they have a common tangent at point *B*.

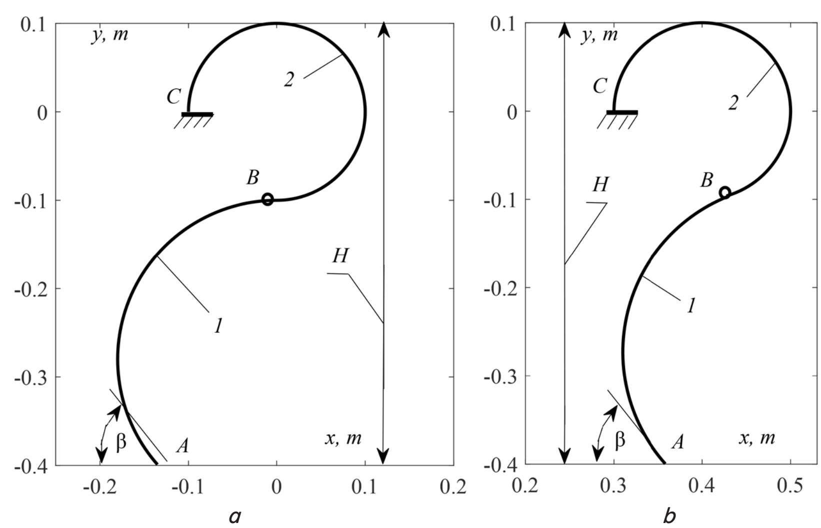

Fig. 4. Two different variants of the elastic axis of the S-shaped riser with some common parameters: *a* – the radius of the *AB* arc $r_1=0.18$ m, its length $s_1=0.415$ m; the radius of the arc *BC* $r_2=0.1$ m, its length $s_2=0.471$ m; *b* – radius of arc *AB* $r_1=0.19$ m, its length $s_1=0.365$ m; the radius of the arc *BC* $r_2=0.1$ m, its length $s_2=0.443$ m

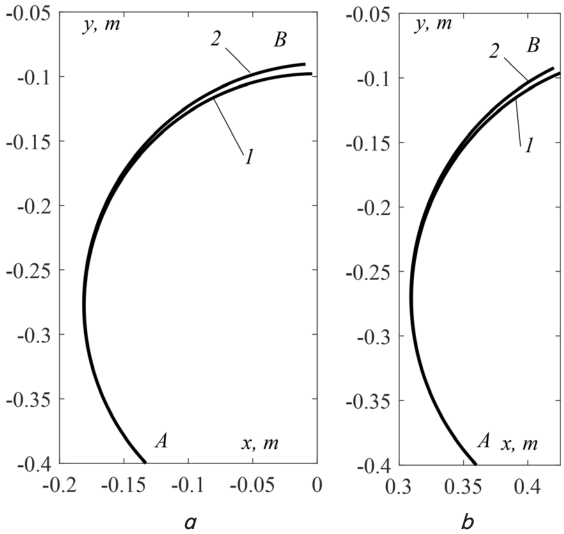

Fig. 5. Elastic axis of the lower part of the riser (arc *AB*) before the deformation – 1 and after the deformation – 2: *a* – the arc of the riser, which corresponds to Fig. 4, *a*; *b* – the arc of the riser, which corresponds to Fig. 4, *b*

5. 2. Analytical description of the bending of an elastic axis of the upper part of the riser

The upper part of the elastic axis of the riser is the arc of the *BC* circle. At point *C*, the riser is attached to the frame of the cultivator (Fig. 4). The resistance force of the soil through the lower part of the riser is transferred to the upper part, which twists, that is, the curvature of the elastic axis of the upper part increases. So, in this case, formula (3) should be used to determine the angle α. It is valid for the case when the force *P* is applied at point *B*. Since it is applied at point *A*, the moment of force $M_1=P_1 \cdot s_1$ is transmitted from the lower part of the riser to the upper part, where s_1 is the length of the elastic axis of the lower part *AB* of the riser, i.e., $s_1=0.415$ m. The force P_1 is the same as that acting on the lower part of the riser, i.e., $P_1=500$ N. Therefore, the additionally applied moment is $M_1=500 \cdot 0.415=207.5$ N·m. Taking into account the additionally applied moment M_1, the angle α is determined from formula (3):

$$\alpha=\int\left(k_0+\frac{P_1 s+M_1}{EI}\right)\mathrm{d}s=k_0 s+\frac{P_1 s^2+2M_1 s}{2EI}. \qquad (7)$$

The curvature is $k_0=1/0.1=10$, the length of the *BC* arc is $s=0.471$ m. Therefore, according to formula (7): $\alpha=270°+9.6°=279.6°$. The rotation of the elastic axis of the upper part of the riser under the action of the total moment occurred by 9.6°. In Fig. 6, *a*, the numerical integration of equations (5) taking into account dependence (7) was used to construct the elastic axis of the upper part of the riser after deformation. Similarly, the same axis is built for the second version of the riser shown in Fig. 4, *b*.

Alignment of the elastic axis after deformation with the initial axis before deformation occurs due to the introduction of appropriate constants during numerical integration, which specify the angle of rotation and the value of movement along the axes.

5. 3. Construction of a solid elastic axis of the riser after its deformation

In Fig. 5, 6, the elastic axes of the riser, which was conventionally divided into two parts, are constructed. To connect them into a single entity, it is necessary to properly move the lower part to the upper one so that the points *B* coincide, and it has a common tangent to both parts of the elastic axis. To do this, the elastic axis of the lower part of the riser is moved along the axes and turned to the desired angle. The angle of rotation is determined from formulas (6) and (7) as an additional angle obtained as a result of the deformation of the elastic axis due to the action of the applied moment. It is the sum of the "extension" angle of 4.2° and the "flexion" angle of 9.6°. Therefore, the total angle of rotation is 13.8°. The previous (in the free state) and the new position of the elastic axis are plotted in Fig. 7. The elastic axis in the free state is marked with the number 1, after deformation – with the number 2. Accordingly, the angle of entry β of the cultivator paw into the soil changes: while in the free state it was 45° (Fig. 4), after deformation it is 45°+13.8°=58.8°.

For the second option (Fig. 7, *b*) according to similar calculations: 45°+13.0°=58°, that is, the angle of entry into the soil after deformation is practically the same. At the same time, there is a significant difference in the height deviation of the riser in a stressed state: in the first case (Fig. 7, *a*) this deviation is 0.04 m, and in the second (Fig. 7, *b*) it is half as much, i.e., 0.02 m.

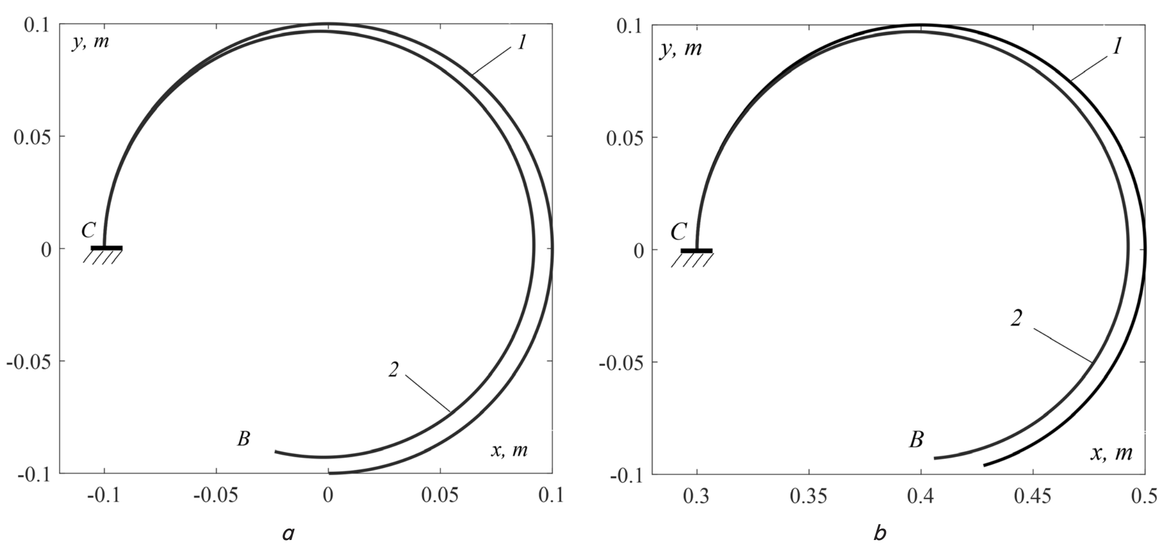

Fig. 6. The elastic axis of the upper part of the riser (arc *BC*) before deformation – 1 and after deformation – 2: *a* – arc of the riser, which corresponds to Fig. 4, *a*; *b* – arc of the riser, which corresponds to Fig. 4, *b*

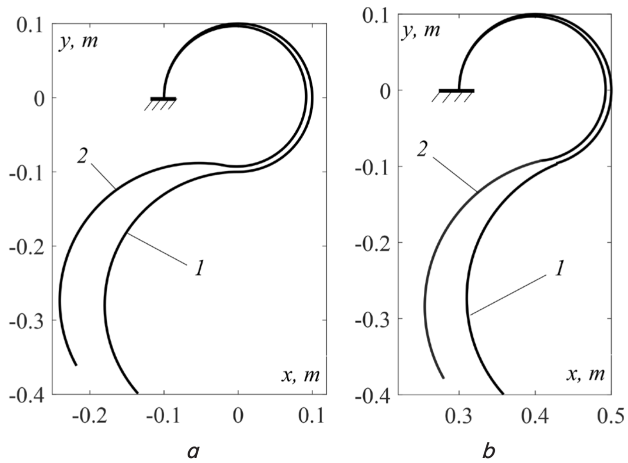

Fig. 7. Comparison of the elastic axes of risers before and after deformation due to the applied force P=500 N: *a* – the total length of the elastic axis of the riser is 0.886 m; b – the total length of the elastic axis of the riser is 0.808 m

6. Discussion of results based on modeling the elastic axis of the S-shaped riser of the cultivator paw

A feature of the proposed method is the conventional division of the riser into two parts. In the literature [1, 2, 7], the calculation of significant deflections of rods is carried out without dividing them into parts since the elastic axis has a regular character of curvature change and is described by one dependence. The elastic axis of the considered S-shaped riser consists of two arcs of circles of different curvature, and these arcs have a different sign of curvature. This leads to the fact that during the operation of the riser, it is deformed in such a way that the curvature of one part decreases, and the other increases.

As a result of the analytical description of the deformation of the elastic axis of each part of the riser, the equations of the dependence of the curvature on the length of the axis were constructed. These equations are similar and consist of two parts: the curvature of the axis in a free state and in a stressed state. The difference between them is the sign before the curvature expression, which increases (3) or decreases (4). By integrating these expressions, the angle between the tangents at the extreme points of the elastic axis is found, the curvature of which decreases (6) or increases (7). At the same time, the action of the additional moment, which is transmitted from one part of the riser to the other, is taken into account. Formulas (6), (7) make it possible to find the angle α of the rotation of the tangent at the extreme point of the axis due to the action of the applied moment. This, in turn, allows one to connect the elastic axes of both parts of the riser after its deformation with a common tangent at the point of connection.

Modeling of the riser carried out in this way allows us to obtain its elastic shape after deformation and compare it with the shape of the elastic axis in the free state (Fig. 7). While the angle of entry into the soil for both cases has practically not changed (58° and 58.8°), the height deviation differs by a factor of two (2 cm and 4 cm). This makes it possible to set the permissible limit of deviation of the paw from the desired depth with the maximum possible effect of the soil on it. If the adopted force P=500 N is considered the maximum possible, then the unevenness of the riser end will be 4 cm in one case (Fig. 7, *a*) and 2 cm in the second (Fig. 7, *b*). This is explained not only by the shape of the riser in a free state but also by the length of its elastic axis. In the second case, it is smaller, so the moment that deforms the riser is also smaller. Due to the fact that the elastic axis of the foot riser is conventionally divided into two sections with a constant curvature, but with the opposite sign, the advantage of this study is obvious in comparison with similar known ones. Our solutions resolve the problem associated with known works, which do not consider the deformation of the riser of the elastic axis, which has a sign-changing nature of its curvature.

The resulting dependences refer to an S-shaped riser, the axis of which in the free state consists of arcs of circles. This is the limitation of our study. A positive point is that, based on the given force acting on the riser, its deviation from the initial position can be determined. However, it is not possible to do the opposite: for a given deviation, find the force that causes this deviation. This is the drawback of the study. Prospect for the development of the research is the use of component arcs of the elastic axis of the riser not only of constant curves but also of variable curvature.

7. Conclusions

1. The equation of the elastic axis of the lower part of the riser has been constructed. The total curvature of the deformed axis consists of the difference of two components: one component is the curvature of the riser axis in a free state and the second component is the curvature acquired as a result of the deformation of the elastic axis as a result of extension. This means that as a result of the applied force to the end of the elastic axis, its total curvature decreases. The lower part of the riser expands, and its elastic axis ceases to be a circle.

2. The equation of the elastic axis of the upper part of the riser in the form of the dependence of its curvature on the length of the arc has been constructed. The curvature consists of the sum of two components: one component is the curvature of the axis of the riser in a free state and the second component is the curvature acquired as a result of the deformation of the elastic axis. This component of curvature grows according to a linear law, as a result of which the elastic axis as a whole grows and acquires the shape of a spiral. At the same time, the transmission of an additional moment from the lower part of the riser is taken into account.

3. Numerical integration of the equations was performed to construct the elastic axes of the upper and lower parts of the riser. They were connected into a single unit according to the first order of smoothness, that is, with a common tangent at the point of connection. To this end, the necessary angle of rotation of the lower part of the elastic axis in relation to the upper part was found based on the obtained expressions. The calculations were based on the actual dimensions of the riser, taking into account the shape of its cross-section and the Young's modulus of the material. This has made it possible to compare the shape of the riser before and after deformation and to determine the deviation of the free end of the riser from its initial position. In the examples given, it is shown that with the same height of the riser, but with different combinations of its constituent parts, into which it is conventionally divided, the deviation in height of the free end differs by a factor of two (2 cm and 4 cm).

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, and the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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