Automatic rigidity adjuster sustaining tillage depth during the work of cultivators with elastic rods

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Abstract. This paper presents the benefits and disadvantages of the elastic cultivator rags usage. The analysis of the bending moment alongside the rod was made. Shear and moment diagrams were designed to describe the horizontal and vertical forces applying on the cultivator foot. While the resistive force is increasing, the tillage depth is decreasing as a result of a rack deformation. The analyzes of scientific papers on tillage depth stabilizing shows that Euler’s equation is the basis for the subsequent calculations. However, this equation defines the sustainability of longitudinally bend compressed rods in mechanics. Thus, the Euler’s equation has limitations and could not be used in full to solve the deformation problem. While studying curved rods movement using Mohr’s integral, the optimal position of the rigidity adjuster was found. The minimizing of the foot instability and excess movement could be done by the change of the rod length and decrease of the bending moment. In order to maintain the constant tillage depth, the rigidity adjuster was installed. The flexible tubes were used as a controller. The change in hydraulic pressure causes the shift of the impact forces applied on the rod and, as a result, the total bending moment decreases. The described above transformations make the method quite comprehensive. The analysis of the force impact deviation depending on the adjuster position is shown in the paper. That evaluations were used in further calculations, and the optimal position of the rigidity controller on the rod was found. The preliminary assessment allowed to conclude that the evenness of the tillage depth depends on the hydraulic pressure and resistive soil force could be compensated.

1. Introduction

Nowadays, the energy and resources efficiency are the main trends in the agricultural industry of Russia [1,2,3]. In order to minimize energy consumption, the cultivators with elastic bands are widely used in horticulture. During the work of the cultivators, the fluctuations arising from the resistance force of the soil. The benefit of such cultivators is the exertion of a vibrational effect on the top soil horizon and minimizing of the soil resistive force. However, the sowing on the clay soils causes elastic deformations and violates soil quality. The question of the sowing soil depth evenness was always of great importance. The no-till technology causes unevenness of the tillage depth and decrease in yield [4].

The cultivator rods have different elements that increase the bending rigidity. Moreover, the used parts have constant stiffness and could not change the downforce while working. In order to maintain the constant tillage depth different rigidity controllers are used in the agriculture [5,6,7]. The most common solution is to use the hydraulic cylinders that promote the foot movement in the vertical
plate. The preliminary mapping of the fields [8], coulter leash angle sensors [9] and ultrasonic sensors [10] are used to determine the tillage depth.

2. Methods
Flexible tubes could be used as a rigidity adjuster and would be placed on the rod. The work of the tubes allows controlling the tillage depth in soils with different physical and mechanical properties. These tubes have been already tested in different load regimes [11], during the tillage [12] and sowing [13], which confirms their capability and efficiency.

The interaction of the cultivator foot placed on the elastic rod and soil surface is shown on figure 1. In case when the rod is not stiff enough, it is deforming and it changes position from type 1 to 2 (figure 1). Such state (deformable) does not allow foot to move deeper as a result the soil tillage depth is decreasing. Moreover, the work of cultivator becomes unstable and the force applied to the rod is increasing. The above-mentioned changes in sowing depth results in uneven seed placement in arable soil horizons.

![Figure 1. Outcome of the soil resistance force impact on the cultivator, where: 1- initial state; 2 – deformable state.](image)

According to the scientific papers and design plans [14,15], one of the methods of the elastic strut rigidity adjustment is to vary its length (figure 2). Euler’s equation describes the length unevenness. Consider using this formula in order to evaluate the critical forces that are influencing on the foot of the cultivator and destabilize its work:

\[
F_{cf} = \left( \pi^2 \cdot E \cdot l \right) / l^2, \text{ N} 
\]

where: \( E \) – modulus of elasticity, MPa;  
\( I \) – moment of inertia of the cross section, mm\(^4\);  
\( l \) – shaft (rod) length, mm.
Figure 2. Elastic rods with the stiffness adjuster.

The changes of the rack rigidity should be applied based on the soil physical properties. To maintain the vibration effect [16], the stiffness regulators are installed near the attachment point because this part has the maximum bending moment.

The equation 1 does not describe the deformation of the elastic rod fully due to the fact that the horizontal force (P) unbalanced the system. However, the equation 1 based on the prediction that the main influential force is longitudinal bending. Thus, the results of the calculations based only on the formula 1 could not be used as they do not describe the process in all details. Therefore, to determine the movements of the cultivator foot, we propose using the Mohr integral:

$$\Delta = \sum_0^n \int_0^z \frac{M_F(z) - M_1(z)}{EI} \, dz,$$

where: $M_F(z)$ – equation of bending moment when the external force impacts the element; $M_1(z)$ - equation of the bending moment when the single force impacts in the studied point.

There is a function (F) that interacts with the cultivator foot at a certain angle ($\alpha$) in the $M_F(z)$ equation (2). Consider analyzing the bending moment alongside the length of the rod. The points of interest on the S-shape rod correspond with the curvature changes (figure 3a). To make a correct calculation, the soil resistance force would be projected to the horizontal and vertical axes. Thus, the bending moments would be calculated using the following equation (3) for the selected points of interests.

$$M(F_x) = F \cdot l_{x1} \cdot \sin \alpha; \quad M(F_y) = F \cdot l_{z1} \cdot \cos \alpha,$$

where: $l_{x1}, l_{z1}$ – distance on axes OX and OZ from the point of forces impact (point 1) to the i point on the rod, mm.

3. Results
Consider the resistance force is equal to $F=1H$, angle ($\alpha$) of the resistance force is $30^\circ$ and usage of the elastic rods parameters as $l$ ($l_{\text{max}}=500$ mm). Shear and moment diagrams for each force application are shown in the figure 3 b, c.
Figure 3. Shear and moment diagram of the S-shaped rack, where: a – points of interest on the rack, b – shear and moment diagram of the horizontal component of the soil resistance force, c - shear and moment diagram of the vertical component of the soil resistance force.

Moment diagram is based on the cross section fibers that are experiencing deformation on the rack. As can be seen from the diagrams horizontal part of the force compresses the fibers when the vertical influences only partially. For example, on the line with the points 1, 2 and 3 the influence of the forces is summarizing, while on the part with nodes 4 - 9 the forces have multi directional impact. In order to make the complete evaluation of the forces, let’s consider the calculation of the total bending moment:

\[
M(F_x, F_z) = \frac{\sum F_x \pm \sum F_z}{L}
\] (4)

In case of contrasting directions of the forces, the sign “−” is used in the above mentioned equation (4).

Figure 4 shows the results of the calculations in the selected points (figure 4).

Figure 4. Bending moment alongside the length of the rack.
The main bending moment is created by the horizontal part of the soil resistance force (figure 4). The largest moment occurs between points 5 and 9. The movement of the point 1 is directly proportional to the bending values and the length of the rack based on the previous equations (2). Therefore, the decrease of these values causes the minimization in the point 1 movement. If the length of the rack is a constant value, then the bending moment can vary by the automatic stiffness adjustment. This rigid adjustment creates an oppositely directed bending moment. The adjustor should be placed on the rod in such a way that the moment is minimized tremendously in points 5, 6, 7 and 8. Shear and moment diagrams are shown on the figure 5.

While applying force \( F_1 \) to the point 5 (fig. 5a), the maximum bending moment occurs in point 6, while it is equal zero in point 7. Thus, the force placed with the horizontal component tends to the maximum in between points 5 and 6 results in the maximum bending moment in the point 7. Consider point 5 as an index 1 when the total bending moment is equal to \( F_1 \) and as an index 2 in the second case. The following equation (5) could be used while evaluating total bending moment from the soil resistance and rigidity adjustor forces. The force is equal to 2H.

\[
M(F_x, F_z, F_1) = 2 \sqrt{F_x^2 + F_z^2 + F_1^2}.
\]  

The results are presented in Figure 6.
As can be seen from the diagram, the total moment is less than $M (F_x, F_z)$ in the case of the second position of the adjuster. Thus, this position can be used as an optimal variant.

The proposed design (fig. 7) consists of a foot (1) mounted on the S-shaped rack (2), which is fixed on the cultivator frame (3) using a bracket (4) and an eye bolt (5). The flexible tubes (6) are used as a rigidity adjuster and are mounted on the cultivator frame. The bracket (7) is fixed on the other side of the frame, so the tubes (6) are mobile relative the rack 2. There is a fitting (8) connecting the inner tube with the hydraulic system of the tractor placed on the top side of the tubes. The flexible tube is a hollow tube of the elliptical cross section (fig. 7 a-a position I). The cross section of the tube is changing when the fluid is supplied to the inner cavity. The form changes from the elliptical to near circle (fig. 7 a-a position II). The force occurs on the free end and directs in the opposite from the point of mount direction. Moreover, there is a controller installed on the stiffness regulator which measured the distance from the frame to the S-shaped rack.

![Figure 7. Elastic rod with the stiffness adjuster.](image)

Tillage works cause constant change in the soil resistive force. Thus, there is a need of the stiffness control during the work. Stiffness adjustment results in the rod’s foot movement stabilization in soil. The sensor 9 sets down distance between the frame and the stand in the proposed model. Based on these values the control block regulates the fluid pressure supplied to the flexible tubes. The increase of the pressure leads to the growth of the stiffness adjustor force ($F_1$). As a result, the soil resistivity forces are compensated and the necessary tillage depth becomes constant.

4. Conclusion

In order to reduce the traction resistance, it is advisable to use elastic rods with a vibrating effect on the soil surface. The main disadvantage of the rods is the tillage depth unevenness caused by the changes in mechanical and physical soil properties. The rigidity adjuster in form of flexible tubes is installed to reduce such unevenness. This controller allows changing the applying force and stabilizing the soil resistance force. As a result, the tillage depth remains constant. The optimal position of the adjuster was evaluated and fixed on the frame, so the flexible tubes properties are used in the most efficient way.

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