On the development of combined tillage working bodies-mechanisms

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Abstract. Tillage working bodies of rigid construction, as a rule, have one degree of freedom. A feature of the working bodies-mechanisms, characterized by a high degree of freedom, is the ability to continuously adapt to changing soil conditions. A working body for subsoiling, consisting of a cutting knife with a built-in drier, to which a mole in the form of a spring of a complex shape is attached, is designed. The time-stretched process of entry into operation of adjacent elements of the combined working body, the periodic deviation of the mole from the rectilinear motion, the continuous change in the diameter of the turns and the length of the mole depending on the difference in the longitudinal hardness of the soil helps to reduce the traction resistance.

1. Introduction

Soil is a multiphase organic medium. Vertical and horizontal mulching [1], maintenance of optimal temperature and water-air regime for the growth and development of plants [2], macro and microorganisms [3], protection of soils from wind and water erosion contribute to the maintenance and increase of its fertility. Waste treatment for seeding, cutting of cracks with simultaneous vertical mulching and formation of moles for infiltration of surface runoff are characterized by high energy consumption. Molders of rigid construction, which are based on a three-sided wedge, carry out deformation of the soil in conditions of blocked cutting at a processing depth exceeding the critical one.

The use of various methods of reducing the traction resistance of working bodies, in particular, the application of antifriction materials, including biological origin to reduce the coefficient of friction [4], is not able to change the nature of cutting. The development of deep diggers with a mole cutter, providing semi-blocked cutting or cutting with a chip in the direction of the free surface, as which the walls of the mole are considered, is an actual scientific problem.

The interaction of the working body with the self-regulating elastic characteristic of the soil in the form of self-oscillations reduces the modulus of soil strength, and, therefore, reduce energy consumption for its loosening.

Studies [5,6] have shown that the variability of the longitudinal hardness of the arable layer has a low-frequency dispersion spectrum, the coefficient of variation is close to 10%, are a broadband process. The arable layer is characterized by a difference in soil hardness, both in magnitude and frequency [7-10]. One of the priority directions of improvement of tillage tools is the use of elastic elements in the working tools. According to [8,9], it allows reducing the resistance of tillage tools by 20%.
Overview of mole plows of different designs helped to identify their advantages and disadvantages, to formulate their requirements for ensuring environmental and energy efficiency when processing soils on the slopes. Experimental studies of the combined tillage working body – mechanism consisting of a cuttings knife with a built-in drainer, inside of which the thrust of the spring mole is mounted [11,12] in the soil channel showed that it is provided with:

- The multi-time entry of work items in the work; at the same time the zone of destruction of the reservoir from the downstream work item should not cover the distance to the previous work item [13]. The latter should be justified taking into account the duration of stress relaxation in the reservoir, which is a function of the speed of the working element, the viscosity coefficient and the modulus of elasticity of the soil.
- Variable distance between adjacent elements depending on the value of translational velocity, physical and mechanical properties of the soil, in particular, the value of longitudinal hardness.
- The possibility of deviation of the mole to the right-left, up-down from the direction of translational speed of the thrust point, moving away or approaching the leading link, that is, the mole should have a wide degree of freedom.
- Changing the diameter of the mole for self-adaptation of the working body when changing the properties of the soil within a wide range.

Despite the widespread use of cultivators with working bodies on an elastic suspension, a generalizing theory to determine and ensure the dynamic characteristics is not developed. Kushnarev A. S. considers the process of oscillations of tillage working bodies as parametric oscillations [6]. In [8] it is proposed to describe the operation of the spring racks of cultivators as undamped oscillations that occur due to the energy supplied to the system from a source having a non-oscillatory nature. Thus, the development of the theoretical foundations of the functioning of tillage working bodies, having the properties of working bodies – mechanisms, is an urgent scientific problem.

The aim of the research is to establish the nature of the relationship between the kinematics of the combined tillage working body-mechanism (CTWBM) with its structural parameters and technological parameters of the cultivated soil.

The objectives of the research are the study of the form of elastic characteristics of providing variable spacing between the elements CTWBM; the derivation of the kinematics of the center of mass of mole plow and analysis; consideration of conditions of formation of the impulse of force from mole plow to stick the knife and of the probability of occurrence of the ultimate strain elastic system CTWBM.

2. Method of research

The research is based on the basic methods of agricultural mechanics, mathematical analysis and theoretical mechanics. The initial premise in the development of working bodies – mechanisms for tillage, we adopted the provision of speeds and accelerations of the Executive working element of the tillage working body, different from similar indicators of the "dead mass" – the equipment frame. This creates the prerequisites for reducing their weight and geometric dimensions. It should be expected that in this case, the mass and volume of the formation involved in the deformation will be small.

According to the shock wave theory, the energy of the shock wave attenuates the faster, the greater the difference between the values of lumps and the higher the degree of crumbling of the soil. So the share of inertial expenses of the working bodies performing direct energy supply to the deformable medium can be reduced. A combination of effects on the environment, separated in time and space, with a non-constant value, periodicity, and duration, is more preferable. The scheme of the combined tillage body-mechanism [11], developed in the Chuvash State Agricultural Academy, taking into account these prerequisites, is presented in Figure 1(a). It consists of a cutting knife 1 with an integrated draining unit 2, inside of which, on an elastic element 5, a thrust spring mole 8 is mounted, with a workpiece diameter \( d \). Considering the advantages and disadvantages of ripper 1 (a), options 1 (b) and 1 (d) were developed. As a result of the experiments, we came to the conclusion that it is possible to expand the limits of adaptation in a design with a conical spring made of increasing diameter wire.
In the first embodiment, the working body was equipped with a Ripper in the form of rigid beams (figure 1a).

The substantiation of the parameters of the mole in the form of a conical spring from a cylindrical rod of constant diameter is given by the method of multi-criteria optimization in terms of traction resistance and overall length in [12]. There is installed base diameter (0.047 m) (figure 1), the diameter of the final turn (0.18 m), the diameter of the wire (0.0083 m), of which the spring mole is made; the radial pitch (0.023 m) and the angle of the cone at the top in the unloaded state (0.035 rad). With a translational speed (1.5 – 2.0) m/s and a diameter \( D_2 = (0.15 – 0.17) \) m, the length of the mole will vary within \((0.25 – 0.31) \) m, and the angle of the cone – within \((15 – 20)^\circ\).

In accordance with the changes in the properties of the soil and the speed mode of operation, the parameters of the working body are continuously changing: the diameter of the turns \( D_1 \) and \( D_2 \), radial and axial steps between the turns; the distance between the traction unit and the working body, its individual working elements. Conditions are created for the formation of different values of speed and acceleration of the center of mass of the spring mole in relation to similar parameters of the traction unit, that is, the equipment frame [8]. There is a continuous change in the value of the cutting angles, crumbling and individual sections attack of each turn. The limits of adaptation of the working body can be expanded in a design with a conical spring made of increasing diameter wire (Figure 1 (c)). Loosening of the soil is performed mainly by shifting, the effect of brushing is realized in perpendicular directions.

3. Results and discussion
To adapt to the changing conditions of the arable layer and the speed mode of the equipment, developed by CTWBM with automatically changing rigidity. The mole is made in the form of a spring of complex...
shape, made of a billet of non-permanent cross-section, attached to the leading link through a system of springs mounted in the traction support. The combination of spring stiffness in the support $c_1^i$ (3, figure 1) and the turns of the mole $c_2^i$ (4, figure 1) (in general, their values are variable), mass $m$, depending on the diameter of the coil and the diameter of the workpiece of the spring mole, contributes to the continuously changing natural frequency $k$, expanding the possibilities of self-adaptation of the working body-mechanism:

$$k^2 = \frac{c_1^i c_2^i}{(c_1^i + c_2^i)m},$$

(1)

At the same time, the possibility of forming various types of elastic characteristics increases. The elastic characteristics of the spring in a support and spring crook system should provide a variable distance between a cutting knife and a mole plow, taking into account the relaxation period of the soil layer, creating conditions for accelerating the masses of the tractor at different times, the implement frame with the cutting knife, and, lastly, the mole plow. Therefore, the system must have a wide range of specific potential energy.

Figure 2 shows the options for changing the potential energy – the dependence of the deformation $h$ on the applied load $Q$: a linear change (1), a progressive increase (2), a progressive decrease (3) and a combined (4), including a progressive decrease at the initial stage and a progressive increase at the final stage.

The static stroke of the elastic characteristic should correspond to the established nature of the movement of the working body, the dynamic stroke reflects the limits of self-adaptation to varying load, and the full stroke informs about the load for strength calculation, allows judging about the possibility to transfer the working body to the transport position by pulling the spring-loaded thrust into the cartridge.

The analysis shows:

- Linear elastic characteristic (curve 1, figure 2) narrows the properties of the self-adaptability of the working body when the hardness of the soil and the speed in a wide range change.
- Low rigidity of the turns $c_2^i$ of the spring mole plow will lead to an increase in the full stroke, at which the mole will stretch to a value limited by the strength of the workpiece, and the outer diameter of the coils will approach the diameter of the draining vessel, which does not contribute to cutting the molehills of the required size. In addition, with a small stiffness of the springs in the support $c_1^i$ and a limited course of thrust, the mole’s “pull in” to transfer to the transport position is not guaranteed. With a falling elastic characteristic (curve 3, figure 2) impacts on the limiter are possible (it is a nut - plug housing drainer).
- The use of a progressively increasing elastic characteristic (curve 2, figure 2) will restrain the limits of the mole self-adaptation over the turns diameter when he passes a significantly over dented strip, for example, a field road.

Thus, with a limited full course of thrust in the support, the desire to reduce rigidity in order to make the combined tillage working body more adaptable conflicts with the need to have sufficient rigidity for self-adaptation. When processing CTWBM soils, characterized by a large differential longitudinal hardness and a significant change in the dynamic viscosity of the arable layer requires high potential energy of the elastic system in the traction support. Rigid "suspension" can lead to an increase in resistance forces on the mole, its peak values will not be "smoothed", the starting resistance will be large, there will be no sufficient way to disperse the "dead" masses of the unit. With soft “suspension”, the likelihood of “breakdown” increases, the number of thrust strikes in the lid of the draining unit embedded in the cutting knife increases. A combined elastic response is required: with a progressive decrease in elasticity at the initial stage (for smooth completion of the transfer to the transport position), a smooth increase in stiffness in the middle part of the stroke, due to the limits of self-adaptation in conditions of little changing load. The progressive increase at the end of the full stroke is dictated by the safe overcoming of foreign bodies, excessively compacted areas of the soil.
To establish the motion law of the spring crook, let us represent it as a single-mass body. In accordance with [10,11], the process of interaction of the soil layer with the cuttings knife and the mole is conditionally divided into stages (phases):

- The phase of uniform motion of the mole with a cuttings knife (figure 3, a).
- The phase of the mole stand – the movement of the mole has stopped, the cutting knife continues to move, the spring in the traction support is compressed (figure 3, c).
- Movement phase: mole plow "catches up" cutting knife, compressed spring in the support is straightened, an over – compacted strip of soil will be overcome.
- Further uniform movement of the mole together with the cutting knife, the spring is in a settled mode of some compression (figure 3, b).

At some point in time, \( t \neq 0 \) the position of the center of mass of the deformer changes by an amount, \( l_1 - l_2 = x - vt \) as a result, the elastic force \( F(t) \) decreases, it is described by the expression

\[
F(t) = R_1 - (x - vt)c .
\]  

(2)

The differential equation of the mass center motion will be represented by an equation of the form:

\[
\ddot{x} + \frac{c}{m} x = \frac{c}{m} v_0 t + \frac{R_1 - R_2}{m} .
\]  

(3)

Solve the equation, taking into account that under the initial conditions, the movement and velocity will be equal to zero: \( x(0) = 0 \); and \( \dot{x}(0) = 0 \):

\[
x(t) = v_0 t - \frac{v_0^2}{k} \sin kt + \frac{R_1 - R_2}{c} (1 - \cos kt) ,
\]  

(4)

here \( k^2 = c/m \) – the natural frequency of oscillations of a single-mass system. The speed of the mole plow changes according to the law:

\[
\dot{x} = v_0 - \frac{v_0 \cos kt}{c} + \frac{R_1 - R_2}{k} \sin kt
\]  

(5)

where \( R_1 \) – the resistance force of the mole to the beginning of the relative motion (in the phase of stagnation); \( R_2 \) – the resistance force at the steady motion of the mole; \( c \) – reduced stiffness; \( k^2 = c/m \) –
natural frequency of oscillations of the system; \( m \) – the reduced mass of the working body and the soil involved in self-oscillation.

If to denote by

\[
\alpha = \frac{k(R_1 - R_2)}{c v_0},
\]

(6)

the stop condition at the time \( t_1 \) can be represented as:

\[
as \sin k t_1 = \cos k t_1 - 1
\]

(7)

After the transformations, we obtain an expression to determine the value of the interval \( t_1 \).

\[
\sin k t_1 = -\frac{2a}{1 + a^2} \quad \text{and} \quad \cos k t_1 = \frac{1 - a^2}{1 + a^2}
\]

(8)

At the moment of stopping the mole, the elastic force from equation (1) will be

\[
F(t_1) = 2R_1 - R_2
\]

(9)

Since \( R_2 < R_1 \), the force at the moment \( F(t_1) \) of stopping will be less than \( R_1 \). Thus, the mole plow after stopping for some time will remain in place until the \( F(t) \) spring force of the spring again reaches the value of the limiting rest force \( R_1 \).

During the time when there is no movement of the mole plow, the force of compression of the spring due to the movement of the frame of the equipment will increase by
\[ \Delta R = R_1 - F(t_1) = 2(R_1 - R_2) \]  

(10)

In this case, the reduction of the spring in the support of the mole (figure 3a) will be:

\[ \Delta l = l_3 - l_2 = \Delta R / c \]  

(11)

The cutting knife with a built-in drains will move at the same distance. Therefore, the duration of the relative immobility of the mole will be:

\[ t_2 = \frac{2(R_1 - R_2)}{c v_0} = \frac{2a}{k} \]  

(12)

Moving the mole and the equipment frame for the period will be:

\[ x_i = v_0 (t_1 + t_2) = T v_0 . \]  

(13)

Thus, by determining \( t_1 \) from the system of equations (8), and then \( t_2 \) from equation (12), one can determine the period \( T \), after which the new cycle of auto-oscillations begins – a spurt of the mole follows. From the expressions of the system (8) we approximate the time:

\[ t_1 \approx \pi/k \]  

(14)

The period of self-oscillation is approximately

\[ T \approx (\pi + 2a)/k \]  

(15)

The value of the second term in the expression (15) increases with decreasing speed of steady motion \( v_0 \). As can be seen from the formula (6), the size of the dimensionless parameter is influenced by the properties of the treated arable layer, the structural parameters of the mole, the stiffness of the spring in the traction support.

Consequently, with a decrease in the speed of steady motion increases the period \( T \), as well as the value of the relative speed of the mole when it moves jerkily (figure 4).

As the speed increases \( v_0 \), the duration of stops decreases, and the movement becomes more uniform. The combined working body will be better suited to work in areas with significant variability in the longitudinal hardness of the arable layer.

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**Figure 4.** Graphs of changing the movement and speed of the center of mass of the mole at various stages of the process of interaction with the soil: a) at a stalk knife speed, equal to \( v_{01} \), b) at a stalk knife speed, equal to \( v_{02} \), with \( v_{01} > v_{02} \). \( x \) – movement, \( x' \) – speed, \( x'_{c-a} \) – speed on the "catch up" phase (figure 3a, 3b, 3c).
The foregoing indicates that the properties of the mole self-adapt to changing soil conditions can be pre-estimated through a period of oscillation, the ratio of the duration of the phases of stagnation and relative motion. These indicators can be controlled by justifying the rational speed of the gun frame, the composition (design and arrangement of elements) of the combined working body, the stiffness of the elastic link. With the increase in the speed of the equipment forward movement, the movement of the mole becomes more uniform. The interaction of the mole with the surrounding soil layer can be represented as a series of short-term pulses.

To establish the character of the pulse interaction of mole plow and stick a knife will determine the acceleration of mole plow, carry out the differentiation of equation (4) and get

$$\ddot{x} = v_0 k \sin kt + \frac{R_2(\eta - 1)}{c} k^2 \cos kt$$

where $\eta = R_1/R_2$ the difference of forces of resistance of the working body before and after the "jerk".

For initial conditions, when time, displacement, and velocity are zero, the acceleration is maximum

$$\ddot{x} = \frac{R_2(\eta - 1)}{c} k^2.$$  \hspace{1cm} (17)

Thus, taking into account $k^2 = c/m$ we have

$$\ddot{x}_{\text{MAX}} = \frac{R_2(\eta - 1)}{m}.$$  \hspace{1cm} (18)

Consequently, the force pulse depends on the mass of the moving part of the combined working body (center of mass of the mole), the stiffness of the spring turns, the frequency of natural oscillations, the resistance drop of the working body due to the rheological characteristics of the soil and the variability of its longitudinal hardness.

The highest pulse corresponds to the state of "extremely compressed spring in the support and extremely elongated spring mole." This phenomenon may occur at the time of overcoming the working body of the soil strip with high longitudinal hardness. The travel speed of the frame may vary by jerk, for example, due to significant irregularities of the support surface, when moving the pit, ridge, or other obstacles. In this case, the structural elements will experience the greatest load. Here is need to estimate the probability of an event’s occurrence.

Suppose that the load that caused the deformation of the springs is represented as an exponential momentum.

We suppose the following:

$$q(t) = 0, \text{ if } t > 0, \hspace{0.5cm} q(t) = q_0 e^{-bt}, \text{ if } t \leq 0,$$  \hspace{1cm} (19)

where $q_0$ – expectation of longitudinal hardness (initial pulse value) (set by experiments [5,6,15], $b$ – pulse damping rate, reflecting the duration of the over-compacted soil band, its elastic-viscous properties, as well as the influence of the elastic characteristics of the working body, is a random variable.

The solution of equation (19) establishes the probability of the mole maximum elongation [14]. This phenomenon will correspond to the critical value of the longitudinal hardness, $q_*$ as a result of overcoming which, due to the elastic properties of the mole, a sharp reduction in its length occurs, and the mole mass center will move with a jerk. With an increase in the rate of decay of the pulse, the jerk will occur at a higher value of the parameter $q_*$.

The estimate of probability $P(*)$ of the mole movement with a jerk at the various probability density distributions $p(q_0,b)$ to define the integration region of instability $F(*)$:
Let us assume that the reduced time of the load \( t^* \) pulses is distributed according to the normal law. The required probability can be calculated by setting different values of the initial load \( q_0 \) intensity according to the formula (20).

\[
P(\star) = \int_{F(t^*)} \int p(q_0, b) dq_0 db
\]  

(20)

Figure 5. The change in the probability of the phenomenon of the mole breakthrough at different positions of the distribution center \( p(q_0, t^*) \).

Both pulse parameters are random numbers. If the probability density obeys the normal law and the dispersion coefficients are constant, then the distribution center will move in the plane of parameters \( q_0 - t^* \). The current applicate of the obtained surface (figure 5) reflects the probability of the phenomenon of "center mass movement of the mole by a jerk". With the distance from the origin, it will increase. Consequently, the frequency and intensity of variability of the longitudinal hardness of the soil in the path of the working body will not always be significantly reflected in the behavior of the spring mole. Some changes in hardness will lead to minor changes in the geometric parameters of the working body. The extinguisher of disturbances is the viscosity of the soil, so some disturbances will cause only the beating of the turns of the working body. The behavior of the mole will also depend on the natural frequency of the dynamic system.

Monitoring of the work of the mole in the conditions of the soil canal, as well as analysis of the results of strain gauging, showed that the process of loosening the soil is periodic. The experiments made it possible to reveal a smooth periodic time-varying change in the value of the resistance of the working body [11].

The nature of the change in the traction resistance of a stalk knife with drainer and ripper rigid design and stalk knife with drainer and conical spring made of constant diameter wire allows us to divide the process into two stages (figure 6). The first stage is the entry into the work, the second stage is the steady movement.

In general, the traction resistance of a stalk knife with both ripper variants is oscillatory in both the first and second stages. The graphs are converging at some points, which indicates uneven deformation of the turns of the spring, both in diameter and in the angle of elevation of the conical helix, as well as the adaptation of the spring mole in the deformable layer. The area under the graph (Figure 6), which expresses the total work of the passage of the stalk knife with drainer and conical spring made of constant diameter, is less than the same indicator of the stalk knife with drainer and ripper rigid design.
4. Conclusion
First developed combined tillage working body – the mechanism for deep subsurface treatment that increase infiltration properties the walls of the wormhole by chipping lumps of soil turns of molehill in the direction of the free surface to the center of the wormhole. The self-oscillating nature of the interaction of the working elements of the spring mole with the soil helps to reduce the work on its loosening, and, consequently, the traction resistance of the working body. Therefore, the combined tillage working body-mechanism for soil-free loosening is an energy-saving working body and contributes to the creation of favorable conditions in the soil for the life of micro and microorganism’s, growth and development of plants.

The nature of the oscillatory motion of the spring mole as part of the combined tillage working body-mechanism is due to the natural frequency of the dynamic system, the technological properties of the soil, the type of agricultural background, the direction of movement in relation to the direction of rows of cultivated crops.

The developed mathematical model reflects the property of a combined tillage working body-mechanism to continuously adapt to changing soil conditions. According to the specific potential energy of the dynamic course of the elastic characteristic, it is possible to justify the sizes of replaceable moles on the basis of the average value of the longitudinal hardness of the soil in the cultivated area of the field. The force impulse from the mole to the cutting knife allows forming a network of primary cracks in the formation located in front of the cutting knife, creating conditions for reducing the overall work of loosening the soil.

The elastic force for the case of an "extremely compressed spring in support and an extremely stretched spring mole", the probability of which is established by expression (20), can be taken as the calculated load for strength calculations. The aim of further research is to test experimentally the adequacy of this expression.

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