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Theoretical Basis of Leveling Tillage in a Paraplow-Type Slanted-Column Chisel Plow

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Abstract

As is known, at present the use of static and dynamic equations alone is insufficient for solving the problem of equilibrium of agricultural units. It becomes necessary to introduce additional forces, which significantly increases the complexity of research in this field. Existing studies are characterized by the fact that when analyzing the stability of a tillage implement based on equilibrium conditions, the standard plow body is considered as the working tool.

Keywords: *equilibrium conditions, tillage unit, analytical method, graphical method, plow layer.*

Introduction

Soil tillage is understood as a set of mechanical operations applied to the soil to improve its fertility and to create more favorable conditions for plant growth and development. Primary tillage includes moldboard and non-moldboard methods of soil loosening. The moldboard method (plowing) is a primary tillage operation in which the treated soil layer is turned over, mixed, and loosened. The non-moldboard method (chisel tillage) is performed at a greater depth but without inverting the soil layer, which in turn reduces soil erosion and promotes moisture accumulation within the profile. Plowing and chisel tillage are carried out in autumn as part of the fall tillage system or sometimes in spring. The application of these methods alters soil density and causes internal redistribution of soil layers within the fertile horizon.

Machines performing the moldboard method of primary tillage include reversible moldboard plows such as the Russian PN-5-35 and similar models produced by foreign manufacturers, offered in various configurations with different working bodies and, accordingly, different working widths.

Machines implementing the non-moldboard method of soil tillage include combined units such as the Russian-made АКПД-6Р, whose foreign analogue is the Amazone TL, as well as flat-cutters and deep rippers (chisels). Among agricultural machines of this type it is worth noting models such as АЧП-2.5 and АГР-2.4 produced in Russia, and the Lemken series manufactured abroad.

All the above-mentioned agricultural machines for primary tillage are classified, depending on the type of aggregation with the tractor unit (MTA), into trailed, semi-mounted, and mounted implements. Mounted agricultural machines, as is known, are 1.5–2 times lighter, significantly simpler in design, and more maneuverable during transportation than trailed ones: to turn them at the end of the field, a strip half as wide is required compared to trailed implements. Therefore, mounted units have higher productivity and lower draft resistance than trailed units of equal working width. Semi-mounted machines, in turn, occupy an intermediate position between mounted and trailed implements in most performance indicators.

Agricultural units, as is known, are subjected during operation to forces of various magnitudes and directions. Some of these forces are active (tractive force, weight), while others arise as a result of the action of active forces and are passive (soil resistance, support reactions, inertial forces). The movement of a tillage unit during operation is generally unstable due to the variability of soil resistance caused by differences in hardness, soil structure, field irregularities, and so on. Therefore, to solve the problem of equilibrium of agricultural units, the use of static and dynamic equations alone is insufficient: additional forces must be included, which significantly increases the complexity of the research. To simplify the problem, researchers typically consider only static equilibrium, which is sufficient to reflect the main aspects of correct implement adjustment, taking into account the relatively low operating speeds of tools used for primary soil tillage.

The equilibrium of agricultural machines is a determining factor in ensuring the stable operation of units used for primary soil tillage [1]. One of the fundamental requirements for tillage implements of any type is achieving high-quality work with minimal energy consumption. Both work quality and energy consumption depend on the overall stability of the units during operation in primary non-moldboard tillage. Instability of the unit leads to poor quality of technological operations, high fuel consumption, and an increased number of maneuvers performed by the tractor.

The number and type of forces acting on agricultural machines during operation determine the stability of tillage units. When these forces are balanced both horizontally and vertically, the operation of the agricultural unit can be considered stable [2–4]. Most studies in this field focus on the equilibrium conditions of plows with various types of aggregation (trailed, semi-mounted, mounted). Many researchers emphasize that the stability of mounted implements is influenced by several factors: the physical and mechanical properties of the soil (composition, texture, structure, and moisture content); the dimensions of the cut and inverted furrow during plowing (depth and width); the tillage speed; and the plow weight. Plow draft resistance has a significant impact on the stable operation of the unit. Additional influences include the interactions between the working bodies (share and moldboard), their attachment to the support, the degree of wear of the cutting edge, the shape and polishing rate of casting surfaces, rolling resistance of wheels, and friction of the share nose against the furrow wall [5–7].

It is also known that soil resistance during plowing has a major influence on the evaluation of tillage unit stability. This is due to the complex and continuous reactions generated during the processes of cutting and breaking the soil on the working surfaces of the plow body. Researchers have established that for proper operation, plows must maintain their designated parameters: working depth and soil-cutting width. This can be achieved if plows possess sufficient stability in both the vertical and horizontal planes, and if the distribution of forces acting on them remains in equilibrium in these two planes [8–10].

Материалы и методы

The study employed methods that make it possible to determine the equilibrium conditions of a system of concurrent forces in either analytical or geometric form. The equilibrium conditions were determined for a mounted five-bottom combined implement designed for layered non-moldboard soil tillage. The analytical determination of equilibrium conditions was carried out by formulating equilibrium equations. The graphical determination of equilibrium conditions was performed by constructing force polygons for the vertical and horizontal projection planes.

As is known from mechanics and statics, for a spatial system of concurrent forces to be in equilibrium, it is necessary and sufficient that the resultant of this system be equal to zero. The equilibrium of a planar system of concurrent forces is established when the algebraic sums of the projections of all forces on each of two arbitrarily chosen coordinate axes lying in the plane of the forces are equal to zero.

If a free body is acted upon by a system of concurrent forces (whether spatial or planar) that is equivalent to zero, this does not necessarily mean that the body will remain at rest relative to the chosen reference system, since the body may continue to move due to inertia. The necessary and sufficient conditions for a free body to be at rest under the action of a system of concurrent forces are as follows:

– the resultant of the system of forces must be equal to zero;

– the initial velocities of all points of the body must also be equal to zero.

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$$N_y = \sqrt{1+\mu^2}\{[mg + R_{1xz}\sin\psi_{ю} + R_{2xz}\sin\psi_p]X_\pi + mgl_2 -$$
$$-[R_{1xz}\cos\psi_{ю} + R_{2xz}\cos\psi_p]Z_\pi + R_{1xz}\left\{\left[h_1(ctg\alpha_{ю} + ctg\psi_{ю}) - l_1\right]\sin\psi_{ю} -\right.$$
$$\left. -H_1\cos\psi_{ю}\right\} + R_{2xz}\left\{\left[L_1 + h_2 ctg\alpha_{ў} - l_1\right]\sin\psi_p\right\}:$$
$$:\left[X_\pi - l_T + \mu(Z_\pi + H_1 - h - 0{,}5d_T)\right], \qquad (1)$$

were μ –rolling coefficient of the support wheels of the improved chisel-type plow

m –mass of the improved chisel-type plow, kg.

g –Acceleration due to gravity, m/s²

X_π, Z_π – respectively, the horizontal and vertical distances from the lower suspension points D (D_1) of the improved chisel-type plow to its instantaneous center of rotation, m;

Solving equations (2) and (3) simultaneously

$$X_\pi = \frac{H_2\sqrt{l_б^2 - (H_3+h-H_1)^2}\left[\sqrt{l_б^2 - (H_3+h-H_1)^2} - X_B\right]}{(H_2 - Z_B)\sqrt{l_б^2 - (H_3+h-H_1)^2} - (H_3+h-H_1)X_B} \qquad (2)$$

and

$$Z_\pi = \frac{H_2(H_3+h-H_1)\left[\sqrt{l_б^2 - (H_3+h-H_1)^2} - X_B\right]}{(H_2 - Z_B)\sqrt{l_б^2 - (H_3+h-H_1)^2} - (H_3+h-H_1)X_B}. \qquad (3)$$

Taking expressions (2) and (3) into account, expression (1) takes the following form

$$N_y = \sqrt{1+\mu^2}\left\{\left[mg + R_{1xz}\sin\psi_{ю} + R_{2xz}\sin\psi_p\right]\times\right.$$
$$\times\frac{H_2\sqrt{l_б^2 - (H_3+h-H_1)^2}\left[\sqrt{l_б^2 - (H_3+h-H_1)^2} - X_B\right]}{(H_2 - Z_B)\sqrt{l_б^2 - (H_3+h-H_1)^2} - (H_3+h-H_1)X_B} + mgl_2 - \left[R_{1xz}\cos\psi_{ю} +\right.$$
$$\left.+(R_{2xz}\right]\frac{H_2(H_3+h-H_1)\left[\sqrt{l_б^2 - (H_3+h-H_1)^2} - X_B\right]}{(H_2 - Z_B)\sqrt{l_б^2 - (H_3+h-H_1)^2} - (H_3+h-H_1)X_B} +$$

$$+R_{1xz}\times\left\{\left[h_1(ctg\alpha_{ю}+ctg\psi_{ю})-l_1\right]\sin\psi_{ю}-H_1\cos\psi_{ю}\right\}+$$

$$R_{2xz}\left\{\left[L_1+h_2(ctg\alpha_p+ctg\psi_p)-l_1\right]\times\right.$$

$$\left.\left.\times\sin\psi_p-(H_1-h_k)\cos\psi_p\right\}-H_1\cos\psi_p\right\}\Bigg\}:$$

$$:\left\{\frac{H_2\sqrt{l_б^2-(H_3+h-H_1)^2}\left[\sqrt{l_б^2-(H_3+h-H_1)^2}-X_B\right]}{(H_2-Z_B)\sqrt{l_б^2-(H_3+h-H_1)^2}-(H_3+h-H_1)X_B}-l_T+\right.$$

$$\left.+\mu\left\{\frac{H_2(H_3+h-H_1)\left[\sqrt{l_б^2-(H_3+h-H_1)^2}-X_B\right]}{(H_2-Z_B)\sqrt{l_б^2-(H_3+h-H_1)^2}-(H_3+h-H_1)X_B}+H_1-h-0{,}5d_T\right\}\right\}.$$

(4)

$$m=qB; \qquad (5)$$

$$R_{1xz}=\frac{R_{1T}}{\cos\psi_{ю}}=\frac{n_1(K_{ю}+E_{ю}V^2)b_{ю}h}{\cos\psi_{ю}}; \qquad (6)$$

$$R_{2xz}=\frac{R_{2T}}{\cos\psi_p}=\frac{n_2\eta(K_p+E_pV^2)b_p(h-h_T)}{\cos\psi_p}; \qquad (7)$$

where q is the mass of the improved chisel cultivator per meter of working width, kg.

Taking expressions (6) and (7) into account, formulas (8)–(9) take the following form:

$$R_{1xz}=(\frac{B}{2a_k}+1)(K_{ю}+E_{ю}V^2)b_{ю}h/\cos\psi_{ю}; \qquad (8)$$

$$R_{2xz}=\frac{B}{a_k}\eta(K_{ў}+E_{ў}V^2)b_{ў}(h-h_T)/\cos\psi_{ў}; \qquad (9)$$

M, R_{1xz}, R_{2xz} If we substitute the values according to expressions (8) and (9) into (4)

$$N_y=\sqrt{1+\mu^2}\times$$

$$\times\left\{\left[qBg+(\frac{B}{2a_k}+1)(K_{ю}+E_{ю}V^2)b_{ю}htg\psi_{ю}+\frac{B}{a_k}\eta(K_{ў}+E_{ў}V^2)b_phtg\psi_p\right]\times\right.$$

$$\times\frac{H_2\sqrt{l_б^2-(H_3+h-H_1)^2}\left[\sqrt{l_б^2-(H_3+h-H_1)^2}-X_B\right]}{(H_2-Z_B)\sqrt{l_б^2-(H_3+h-H_1)^2}-(H_3+h-H_1)X_B}+qBgl_2-$$

$$-\left[(\frac{B}{2a_k}+1)(K_{ю}+E_{ю}V^2)b_{ю}h+\frac{B}{a_k}\eta(K_p+E_pV^2)b_ph\right]\times$$

$$\times \frac{H_2(H_3+h-H_1)\left[\sqrt{l_б^2-(H_3+h-H_1)^2}-X_B\right]}{(H_2-Z_B)\sqrt{l_б^2-(H_3+h-H_1)^2}-(H_3+h-H_1)X_B}+$$

$$+(\frac{B}{2a_k}+1)(K_ю+E_ю V^2)b_ю h\left\{\left[h_1(ctg\alpha_ю+ctg\psi_ю)-l_1\right]tg\psi_ю-H_1\right\}+$$

$$+\frac{B}{a_k}\eta(K_p+E_ў V^2)b_p h_T\left\{\left[L_1+l_2+h_3(ctg\alpha_ў+ctg\psi_p)-l_1\right]tg\psi_p-H_1\right\}\Bigg\}:$$

$$:\left\{\frac{H_2\sqrt{l_б^2-(H_3+h-H_1)^2}\left[\sqrt{l_б^2-(H_3+h-H_1)^2}-X_B\right]}{(H_2-Z_B)\sqrt{l_б^2-(H_3+h-H_1)^2}-(H_3+h-H_1)X_B}-l_T+\right.$$

$$\left.+\mu\left\{\frac{H_2(H_3+h-H_1)\left[\sqrt{l_б^2-(H_3+h-H_1)^2}-X_B\right]}{(H_2-Z_B)\sqrt{l_б^2-(H_3+h-H_1)^2}-(H_3+h-H_1)X_B}+H_1-h-0{,}5d_T\right\}\right\}. \quad (2.44)$$

If these two conditions are satisfied, the body can be considered to be in equilibrium (in this case, the equilibrium conditions of a free body completely coincide with the equilibrium conditions of a free material point). However, sometimes the equilibrium of the body under consideration is understood as its motion due to inertia, not just its state of rest. Therefore, in statics, problems are solved not only for bodies at rest but also for bodies moving due to inertia.

If constraints are applied to the body, by adding the forces of reaction of these constraints to the active forces applied to the body, it can be considered as free (axiom of constraints). In most cases, in statics problems, for certain known active forces applied to a constrained body, it is required to determine the unknown forces of constraint reactions, assuming that the body is at rest and, therefore, all applied active forces and constraint reaction forces are balanced [11].

When solving such problems, if the lines of action of all forces applied to the body, including the reaction forces, intersect at a single point, the equilibrium conditions of a system of concurrent forces must be used in either analytical or geometric form.

In the analytical method, the desired magnitudes are determined from the equilibrium equations, in the left-hand sides of which, in addition to the projections of known active forces, the projections of unknown constraint reaction forces are included. It should be noted that the relations that include projections of constraint reaction forces are called equations of equilibrium, whereas those relations that do not include projections of constraint reaction forces are called conditions of equilibrium. If the body is constrained, the number of equilibrium conditions is equal to the number of degrees of freedom of the body, i.e., the number of independent displacements that the body can undergo.

In the graphical method for a system of concurrent forces, the desired constraint reaction forces or other unknown quantities in the problem are determined by constructing a closed force polygon or purely graphically, either by drawing this force polygon to a precise scale or by calculating its sides according to the rules of geometric trigonometry.

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Research Results

The study established that tillage implements generally have an excessive number of constraints (supports). An equilibrium condition was obtained for the forces acting on a tillage implement with working bodies for layered non-moldboard soil treatment, which has twelve constraints: five shares, each with two constraints, and two support wheels, each with one constraint. The reactions from interaction with the soil for these supports must remain positive.

During operation, the supports of agricultural machines consist of commonly accepted structural elements such as shares, depth-limiting wheels, and mechanisms for aggregation with the tractor.

Considering that the mass of the tractor-implement unit (TIU) is significantly (approximately ten times) greater than the mass of the implement being attached, when determining the equilibrium conditions of the latter, the number of degrees of freedom is defined relative to the tractor frame [14].

The greatest number of degrees of freedom is possessed by a trailed agricultural machine, as it is connected to the tractor at a single point (the hitch point), allowing rotation along the longitudinal, transverse, and vertical axes passing through this point. The hinged attachment of the trailer to the implement frame also allows translational movement of the implement relative to the tractor in the vertical direction. Thus, trailed implements have four degrees of freedom relative to the tractor.

Mounted agricultural machines, aggregated with the tractor via a three-point hitch mechanism, have two degrees of freedom relative to the tractor — rotation about the y and z axes. Reducing the degrees of freedom of a mounted implement relative to the tractor to one is not feasible, as this could lead to damage of the attached implement (if rotation about the y-axis is restricted) or loss of tractor controllability (if rotation about the z-axis is restricted). Allowing three degrees of freedom (rotation about the x, y, and z axes) is reasonable only for multi-bottom machines (five or more bottoms), when independent adaptation of the implement and tractor to the field relief in the transverse plane is required.

Semi-mounted agricultural machines, depending on the aggregation method with the tractor, have three or four degrees of freedom relative to the tractor.

As a rule, agricultural implements have an excessive number of constraints. For example, a mounted five-bottom combined implement for layered non-moldboard soil treatment has twelve constraints: five shares, each simultaneously experiencing two forces (one parallel to the z-axis and another parallel to the y-axis) due to contact with the bottom and wall of the furrow, and two support wheels, each adding one additional constraint. The number of degrees of freedom of such an implement relative to the TIU is two; therefore, in this case, the number of redundant supports is ten.

Thus, modern agricultural machines are multi-operational, statically indeterminate systems, which complicates their adjustment during operation and makes it practically impossible to perform force calculations without introducing additional assumptions. Therefore, for calculations, the following assumptions are made:

-the shares of the implement do not contact the furrow bottom, corresponding to the case of a chisel-type share;

-all implement bodies and shares are uniformly loaded;

-the soil-to-steel friction coefficient (f) and the wheel rolling resistance coefficient are known const for varying wheel loads).

Equality of forces applied to the working surface of each bottom allows replacement of the forces and moments acting on individual bottoms with a resultant force and total moment applied to the central bottom of the implement. Similarly, the forces applied to the shares of the implement are replaced by a resultant force (F) applied to the share of the central bottom.

Determination of forces acting on the tillage implement can be performed by analytical and graphical methods [15].

Since wheels and shares act as unilateral constraints, the equilibrium conditions of the implement during operation require that the reactions of these supports always remain positive.

A check of operational stability is performed twice:

for the case of sharp shares, when the angle, characterizing the inclination of the force (R_{xz}), is positive;

for worn (blunt) shares, when the angle is negative.

The main force load (Q) during operation is applied to the front support wheel; therefore, the construction of the force polygon is referenced to the projection points of forces relative to the front support wheel. The rear support wheel is included in the implement design to enhance frame stability parallel to the plow layer and to reduce the likelihood of gliding effects [16].

Discussion and Conclusion

Based on the results of the study, it can be noted that modern agricultural machines are multi-operational, statically indeterminate systems. As a result, the process of their adjustment during operation becomes more complex, and performing force calculations without introducing additional assumptions is practically impossible. For the sake of simplification, accuracy, and the most visual representation, the problem was solved by analyzing closed force polygons, with a methodology provided for constructing them both for equilibrium conditions in the horizontal and vertical planes.

The study established that tillage implements have an excessive number of constraints (supports). A mounted five-bottom combined implement for layered non-moldboard soil treatment has twelve constraints: five shares, each simultaneously experiencing two forces (one parallel to the z-axis and another parallel to the y-axis) due to contact with the bottom and wall of the furrow, and two support wheels, each adding one additional constraint. While the number of degrees of freedom of such an implement relative to the tractor-implement unit (TIU) is two, the number of redundant supports in this case is ten.

The equilibrium condition of the implement relative to the plow layer requires that the reactions received from the supports, depth-limiting wheels, and shares of the implement remain always positive.

The determination of forces acting on the tillage implement was performed using both analytical and graphical methods.

In the analytical method, the desired magnitudes were determined from the equilibrium equations, whose left-hand sides included, in addition to the projections of known active forces, the projections of unknown constraint reaction forces. Substitutions and simplifications were then made in the resulting equilibrium equations, after which calculations were carried out using standard methods for solving systems of linear equations.

In the graphical method for a system of concurrent forces, the desired constraint reaction forces or other unknown quantities were determined by constructing a closed force polygon. The graphical determination of forces acting on the mounted tillage implement was performed in both the vertical and horizontal projection planes. Constructing force polygons provides more accurate and visually clear results than sequentially summing the forces acting on the implement in a schematic diagram.

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