Directional Stability of an Agricultural Tractor

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The discrepancy between the plow width and the tractor width leads to the asymmetry of plowing units. The geometry of the plowshare surface of the moldboard plow contributes to the generation of lateral forces on the working tool. All this leads to the imbalance of the tool and the deviation of the tractor from straight-line movement during plowing. To maintain straight-line movement, the driver has to adjust the machine every 5-10 meters, which is highly tiresome. To study the causes of lateral slips of the plowing unit, we constructed a mathematical model, which consists of the equations of controlled movement and equations of the tractor's uncontrolled shear under the action of external forces from the plow. The description of the force interaction of the drive with the ground is based on the mathematical theory of friction, taking into account anisotropy and elastic properties in contact. Based on the passive shear model, we constructed a hodograph diagram of the maximum tractor shear force from the side of the working tool. We found that the shear force reaches its maximum friction value only in the case of a translational shear, when its line of action passes through the tractor's center of gravity. In all other cases, the shift (slip) of the tractor is caused by a lower force. We formulated the features and assumptions of the model as applied to caterpillar and wheeled tractors. As a result, we found that, regardless of the direction of the lateral displacement of the plow's traction resistance, the tractor is slipped towards the plowed field. The result of the numerical experiment showed that the main reason for the slip of the wheeled plowing unit is the difference in soils along the sides of the tractor but not the deviation of the plow traction resistance.

Keywords: *directional stability; mathematical model; lateral slip; moldboard plow; ground contact; plowing unit; mathematical theory of friction.*

1. INTRODUCTION

The initial step to a good harvest is high-quality soil treatment [1]. Today, modern agriculture includes various pre-seeding treatment technologies. However, the main method is still traditional plowing with a moldboard plow, which has a positive effect on the further growth and development of plants [2]. In terms of energy intensity, plowing takes 30–35% of the entire energy consumption in field cultivation [3]. The arable layer inversion technology does not only cuts and embeds weeds to a depth inaccessible for germination but also ensures mixing of soil layers and protects it from infectious agents [4].

The discrepancy between the plow width and the tractor width leads to the asymmetry of plowing units. When the plowing unit is in operation, a turning moment is created from the side of the working tool, which deflects the tractor from straight-line movement [5]. To maintain straight-line movement, the driver has to constantly adjust the machine. In wheeled tractors, the impact on the steering wheel is 15-20 times in a 100-meter travel section [6]. In caterpillar tractors, the impact on the friction control lever is every 4–6 m of the unit travel [7]. This leads to the operator's increased fatigue and a decrease in the productivity of up to 10-15% [8]. The main reason for the slip of the plowing unit from the straight-line direction is the impact of the plow on the tractor [9–10]. The composite surface of the moldboard plow leads to a deviation of the normal resistance force P by a certain angle $\beta=15^{o}\ldots25^{o}$ relative to the longitudinal axis of the tractor [11]. To compensate for the lateral component P_y of the plow resistance force, a landside plate is installed in the horizontal plane. The length of the plate is limited by the technological process and the structural dimensions of the plow. The friction of the landside plate consumes up to 17% of the total traction resistance of the tractor, which makes us look for other ways of balancing the plow in the horizontal plane [12].

Studies of the directional stability of s tractor unit during plowing began long time ago [13–15]; however, this issue remains relevant today [16–18]. The solution to the problem of the directional stability of a plowing unit is often limited by the balance of only one working tool (plow) [12, 19]. At the same time, studying the movement of the entire plowing unit in general will allow us to understand better the causes of the side slip of the machine. We will construct a mathematical model

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of the unit's slip to assess the influence of each factor on the deviation from straight-line movement.

The purpose of the researchis to construct a mathematical model of the plowing unit movement allowing us to assess the influence of various factors on the directional stability of a tractor with an asymmetric external load.

2. MATHEMATICAL SLIP MODEL

The movement of the plowing unit under the action of eccentric resistance forces from the plow side is a combination of controlled straight-line movement and a passive uncontrolled shift [20].

The controlled movement equations, taking into account small lateral deviations and low motion speeds, can be written in the form of ordinary curvilinear integrals [21]:

$$\left.\begin{aligned} x_c &= \int_0^T V cos\left(\int_0^t \frac{V}{\rho} d\tau\right) dt \\ y_c &= \int_0^T V sin\left(\int_0^t \frac{V}{\rho} d\tau\right) dt \end{aligned}\right\} \qquad (1)$$

where x_c, y_c are the coordinates of the unit's center of mass in a fixed reference, t=0…T is the movement time; V is the speed, ρ is the radius of the trajectory curvature.

The uncontrolled shift equations are the equations of the power balance of the entire plowing unit (Fig. 1).

$$\left.\begin{aligned} F_{x1} + F_{x2} - P_f - Pcos &= 0, \\ F_{y1} + F_{y2} - (Psin - R_{б}) &= 0, \\ (y_k + y_1 - 0.5B)\,Pcos - x_k\,(Psin - R) & \\ + y_1 P_{f1} + y_2 P_{f2} - \sum M_i &= 0, \end{aligned}\right\} \qquad (2)$$

where P is the resulting plow resistance force; β is the tilt angle of the resistance force to the longitudinal axis of the tractor; x_k, y_k are the coordinates of point K of applying the resulting resistance force of the plow relative to the tractor's center C of mass; R_O is the resistance force of the landside plate; B is the tractor wheel track; P_{fi} are the forces of resistance to the movement of the i caterpillar band (side); y_i are the coordinates of the instantaneous center O of sliding of the contact area of the i caterpillar band (side); F_{xi}, F_{yi}, M_i are the total force factors in the contact of each caterpillar band (side) with the ground [22].

The force factors in the drive-ground contact are essentially friction forces.A shift relative to the ground is observed when the friction forces reach their limiting value. There is no relative slip in cases of all lower values of the forces in the contact. The mathematical theory of friction [23] allows us to determine the maximum (limiting) values of the force factors in the contact of the drive with the ground, when the external force P causes a rotational shift relative to some instantaneous sliding center O. Then, the force factors F_{xi}, F_{yi}, M_i in the i contact are the functions of the unknown coordinates x_i, y_i of the instantaneous sliding center O in the coordinate system linked with the geometric contact center [24]:

$$\left.\begin{aligned} F_{xi} &= q \frac{\mu_i (y_i -)}{\sqrt{(y_i -)^2 + (x_i - \gamma)^2}} d\gamma d, \\ F_{yi} &= -q \frac{\mu_i (x_i - \gamma)}{\sqrt{(y_i -)^2 + (x_i - \gamma)^2}} d\gamma d, \\ M_i &= q \mu_i \sqrt{(y_i -)^2 + (x_i - \gamma)^2}\, d\gamma d \end{aligned}\right\} \qquad (3)$$

where μ_i is the coefficient of friction in the i contact with the ground; x_i, y_i are the coordinates of the instantaneous sliding center of the i ground contact area in the coordinate system linked with its geometric center; γ, η are the present coordinates of the contact points.

The introduction of a variable friction coefficient μ_i under the integral of the force factors F_{xi}, F_{yi}, M_i allows us to take into account the elastic properties at each contact point [25] and establish the relationship between the force factors and the radius ρ of the trajectory curvature:

$$\left.\begin{aligned} {}_{xi} &= {}_{mxi}\ \text{th}\left[\frac{(y_i -)}{(\rho 0.5B + y_i)}\right], \\ {}_{yi} &= {}_{myi}\ \text{th}\left[\frac{(x_i - \gamma)}{(\rho 0.5B + y_i)}\right], \end{aligned}\right\} \qquad (4)$$

where $\mu_{mxi} = \mu_{myi}$ is the maximum coefficient of friction in the longitudinal and transverse directions; th is the hyperbolic tangent function; λ is the empirical coefficient characterizing the elastic properties of the ground; ρ is the radius of the trajectory curvature.

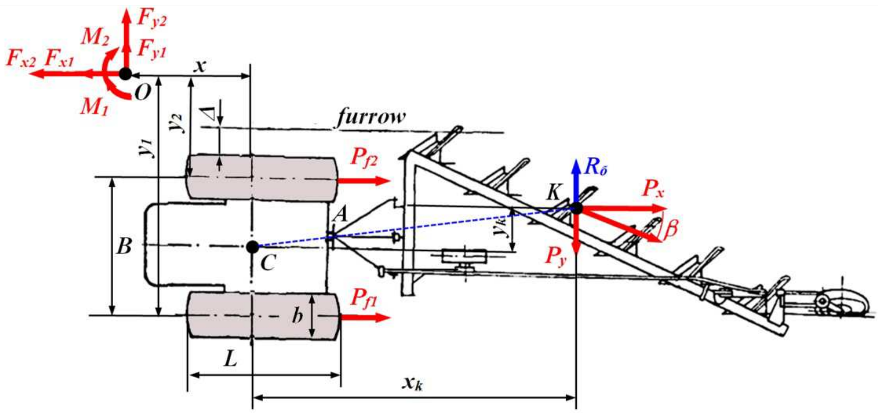

Figure 1. A diagram of the forces acting on the plowing unit

Characteristics of the caterpillar unit movement. The length of the caterpillar band-to-ground contact L is much larger than its width b. This allows us to replace the double integral in equations (4) with a single one with an error of no more than 2% [26]. In this case, the average normal pressure in the contact is $q = G/2Lb$.

A caterpillar plow tractor generally moves along the unplowed part of a field at a certain distance from the edge of the furrow (provided that the furrow wall is not shedding) (Fig.2a), which allows us to accept identical ground conditions under both caterpillar bands.

However, due to grousers, the interaction of the caterpillar band with the ground acquires anisotropic properties, which can be expressed by introducing different friction coefficients μ_i in the longitudinal μ_{xi} and transverse μ_{yi} directions [26]. Because of the transverse arrangement of grousers, there is almost no elastic deformation of ground in this direction, since the ground cut begins almost at once $\mu_{yi} = \mu_{myi}$.

As a result, the force factors F_{xi}, F_{yi}, M_i are as follows:

$$\left.\begin{aligned}
F_{xi} &= \frac{G}{2Lb}\int_{-L/2}^{L/2} \frac{\mu_{mxi} y_i \operatorname{th}\left[\dfrac{(x_i-\gamma)}{(-\rho 0.5B+y_i)}\right]}{\sqrt{y_i^2+(x-\gamma)^2}}d\gamma, \\
F_{yi} &= -\frac{G}{2Lb}\int_{-L/2}^{L/2} \frac{\mu_{myi}(x-\gamma)}{\sqrt{y_i^2+(x-\gamma)^2}}d\gamma, \\
M_i &= \frac{G}{2Lb}\int_{-L/2}^{L/2} \frac{\mu_{mxi} y_i^2 \operatorname{th}\left[\dfrac{(x_i-\gamma)}{(-\rho 0.5B+y_i)}\right]+\mu_{myi}(x-\gamma)^2}{\sqrt{y_i^2+(x-\gamma)^2}}d\gamma.
\end{aligned}\right\} \quad (5)$$

a)

b)

Figure 2. Movement of (a) a caterpillar and (b) wheeled tractor during plowing

Characteristics of the wheeled unit movement. The technology of plowing with a wheeled plowing unit implies the movement of the wheels of one side along the bottom of the furrow (Fig. 2b). This results in a constant lateral tilt of the machine. The consequence is a different normal load on the sides determined by [12]:

$$q_i = \frac{G}{2ab}\left(\frac{\cos\alpha}{2} \pm \frac{h\sin\alpha}{B}\right) \quad (6)$$

where the "+" sign is used for the lower side moving in the furrow, the "–" sign is used for the upper side moving along the virgin soil; α is the tilt angle of the tractor, h is the height of the tractor's center of mass; ab is the length and width of the wheel track.

The lateral tilt of a wheeled tractor leads to a redistribution of the weight load between the sides (6). According to calculations, the tilt angle is 5–6°, which corresponds to the 13–15% difference in the normal load. A change in the normal load on the wheels leads to a change in the size of the contact patch (Fig. 3), increasing the track length a, while its width b remains unchanged [27]. Besides, the movement on a loose ground contributes to an additional increase in the contact patch of one of the tractor sides [28].

The symmetrical arrangement of the tire tread pattern allows us to accept identical friction coefficients in the longitudinal and transverse directions $\mu_{mxi} = \mu_{myi}$. The elastic properties in the contact are provided in the longitudinal direction due to the crushing of the ground, and in the transverse direction - due to the deformation of the tire. Besides, the wheels of different sides move on the ground with different properties. Taking into account the aforesaid, the force factors F_{xi}, F_{yi}, M_i (3) will be as follows:

$$\left.\begin{aligned}
F_{xi} &= q_i \int_{\frac{-b}{2}}^{\frac{b}{2}} \left(\int_{\frac{-L-a}{2}}^{\frac{-L+a}{2}} \frac{\mu_{mxi}(y_i-)\operatorname{th}\left[\dfrac{(y_i-)}{(-\rho 0.5B+y_i)}\right]}{\sqrt{(y_i-)^2+(x_i-\gamma)^2}} d\gamma + \int_{\frac{L-a}{2}}^{\frac{L+a}{2}} \frac{\mu_{mi}(y_i-)\operatorname{th}\left[\dfrac{(y_i-)}{(-\rho 0.5B+y_i)}\right]}{\sqrt{(y_i-)^2+(x_i-\gamma)^2}} d\gamma \right) d\eta \\
F_{yi} &= -q_i \int_{\frac{-b}{2}}^{\frac{b}{2}} \left(\int_{\frac{-L-a}{2}}^{\frac{-L+a}{2}} \frac{\mu_{mi}(x_i-\gamma)\operatorname{th}\left[\dfrac{(x_i-\gamma)}{(-\rho 0.5B+y_i)}\right]}{\sqrt{(y_i-)^2+(x_i-\gamma)^2}} d\gamma + \int_{\frac{L-a}{2}}^{\frac{L+a}{2}} \frac{\mu_{mi}(x_i-\gamma)\operatorname{th}\left[\dfrac{(x_i-\gamma)}{(-\rho 0.5B+y_i)}\right]}{\sqrt{(y_i-)^2+(x_i-\gamma)^2}} d\gamma \right) d \\
M_i &= q_i \int_{\frac{-b}{2}}^{\frac{b}{2}} \left(\begin{aligned} &\int_{\frac{-L-a}{2}}^{\frac{-L+a}{2}} \frac{\mu_{mi}}{\sqrt{y_i^2+(x-\gamma)^2}} \left[\begin{aligned} &(y_i-)^2\, th\left[\frac{(y_i-)}{(-\rho 0.5B+y_i)}\right]+ \\ &+(x-\gamma)^2\, th\left[\frac{(x_i-\gamma)}{(-\rho 0.5B+y_i)}\right] \end{aligned} \right] d\gamma + \\ &+\int_{\frac{L-a}{2}}^{\frac{L+a}{2}} \frac{\mu_{mi}}{\sqrt{y_i^2+(x-\gamma)^2}} \left[\begin{aligned} &(y_i-)^2\, th\left[\frac{(y_i-)}{(-\rho 0.5B+y_i)}\right]+ \\ &+(x-\gamma)^2\, th\left[\frac{(x_i-\gamma)}{(-\rho 0.5B+y_i)}\right] \end{aligned} \right] d\gamma \end{aligned} \right) d
\end{aligned}\right\} \quad (7)$$

where μ_{mi} is the maximum friction coefficient in the i side-to-ground contact; f_i is the coefficient of the i side rolling resistance.

Figure 3. A change in the dimensions of the wheel-to-ground contact depending on the normal load

Coupling equations. Uncontrolled movement (without the driver's control action) is characterized by a fixed relative movement of the drive supports (wheels or caterpillar bands) corresponding to a single sliding center (point O) for the contacts of both sides [8,29], which allows us to write the missing coupling equation:

$$y_1 = y_2 + B \tag{8}$$

where 1,2 is the caterpillar band (side) index.

A quasi-static slip model includes the system of equations (1–8), where the unknown radius ρ of the trajectory curvature is unambiguously determined [23] from the equilibrium equations (2), taking into account formulas (3–7). Thus, each value of the external plow resistance force P corresponds to its own radius ρ of the trajectory curvature and the instantaneous sliding center O.

We will conduct a numerical experiment for a detailed analysis of the impact of various factors on the movement trajectory of a plowing machine-tractor unit.

3. RESULTS OF THE NUMERICAL EXPERIMENT

The plow resistance force is characterized by the module P, direction, and point of application.

The determination of the plow resistance force module P is a very complicated task, depending on many factors: the type of the ground being treated, the depth of treatment, the speed of movement, the weight, shape and width of the plow (number of bodies), etc. [30]. The transverse component P_y is generally compensated by the response of the landside plate R_O. Its increase leads to an increase in the length of the landside plate and, consequently, an increase in the coverage and tractive effort. The correct choice of the landside plate size allows us to achieve the equality [12]. $P\sin\beta = R_O$. Then, the uncontrolled shear is preconditioned only by the lateral displacement y_k of the longitudinal component P_x of the plow resistance force.

The longitudinal component P_x is perceived by the traction force ΣF_{xi} of the tractor characterized by friction. Consequently, there is no side slip (cross slip) when the force P_x is less than the limiting value according to the equilibrium conditions. The limiting (maximum) value of the shear force P corresponds to a certain direction (line of action) [29]. F.A. Opeiko proved the uniqueness of the connection betweenthe ultimate strength and the line of action.

The direction of the shear force is determined by the shape of the ploughshare surface and is taken into account through the tilt angle β of the resultant plow resistance force P to the longitudinal axis of the tractor [12]. For a comprehensive study of the dependence of the limiting force P on the direction, on the basis of the equilibrium equations (2), we constructed a hodograph diagram of the shear force using the example of a caterpillar tractor (Fig. 4).It allows us to determine the limiting values of the shear force P_{max} and its components P_x and P_y for each line of action. The accounting of the anisotropy reduces the values of the maximum shear force and rotates the hodograph diagram towards a lower friction coefficient by an angle δ, which depends on the ratio of the friction coefficients in the longitudinal μ_{mx} and transverse μ_{my} directions.

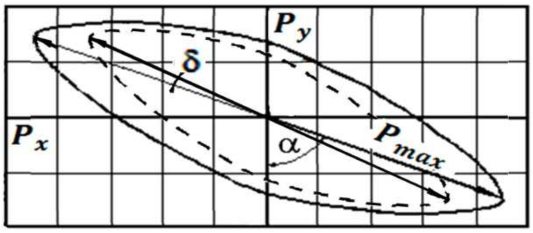

Figure 4. Shear force hodograph diagram

The analysis showed that at a passive shear, the maximum value of the shear force $P_{max} = G(u - f)$ is possible only in the case of a straight-line shear, when the line of the force action passes through the machine's center C of the mass. This private case characterizes translational sliding. The movement trajectory, taking into account the slip, is a straight line (line 1 in Fig. 5) and is provided by a displacement of the hitch point relative to the longitudinal axis of the tractor [31–32]. In all other cases, there is an instantaneous rotational shear, and the shear force is less than its maximum value $P < P_{max}$. The presence of the instantaneous rotational shear leads to the fact that if the driver takes no control action, the value of the lateral deviation y_c quadratically increases with an increase in the distance covered x_c (lines 2-4 in Fig. 5)

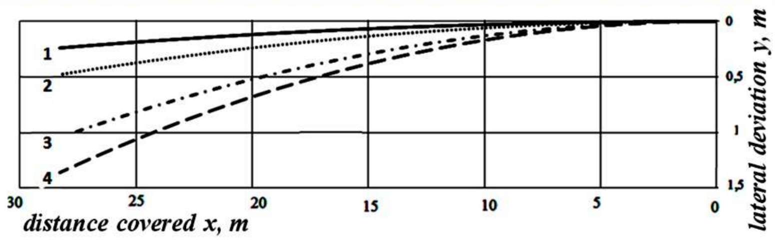

Figure 5. Movement trajectories of the plowing unit: 1 - translational slip, 2 - slip caused by the displaced traction resistance of the plow, 3 - slip caused by different ground contact conditions; 4 - total slip

An increase in the lateral displacement y_k (the arm of the force action) leads to an increase in the rotating effect and, consequently, to an increase in the side slip of the tractor. The calculations have shown that regardless of the direction of the lateral shift y_k, the deflection of the tractor was always observed in one direction - towards the plowed field.

Different movement conditions of the tractor sides have the maximum impact on the directional stability of the plowing unit. The calculations have shown that due to the difference in the coefficients of friction μ_i and of rolling resistance on the sides f_i, the tractor loses its directional stability even when there is no impact of the external load from the plow. In this case, the lateral deviation (line 4 in Fig. 5) exceeds the slip value from the plow resistance force (line 2 in Fig. 5).

4. CONCLUSIONS

The mathematical slip model consists of the equations of controlled straight-line movement and the equations of uncontrolled passive shear under the influence of external forces, which represent the power balance of the plowing unit.The interaction of the tractor drive with the ground is presented on the basis of the mathematical theory of friction, taking into account the anisotropy and elastic properties in the contact.

Each line of action of the shear force has a corresponding limiting value. When the force is less than this value, there is no sides hear and slip of the tractor from straight-line movement. The shear force reaches its maximum friction value when its line of action passes through the machine's center of mass. In this case, there is a translational shear, and the slip trajectory is a straight line.When the line of action of the shear force does not pass through the tractor's center of mass, the static balance is violated at its lower value, and an instantaneous rotational shear occurs. In this case, the value of the lateral deviation from the straight-line direction quadratically increases depending on the distance covered. The interaction anisotropy additionally reduces the value of the limiting shear force.

The movement of one side of the tractor along the bottom of the furrow creates different conditions in the wheel-to-ground contact. The normal load, track size, friction, and rolling resistance coefficients differ on the sides, which leads to the loss of the machine's directional stability (even if there is no resistance on the plow).

In the future, the proposed mathematical model can be used as the basis for the development of an automatic (unmanned) tractor control system.

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NOMENCLATURE

a,b	wheel contact length and width
B	the tractor wheel track
L	the longitudinal tractor base
H	the height of the tractor's center of mass
F_x, F_y, M	the force factors in the contact with the ground
P	the resulting plow resistance force
P_f	the forces of resistance to movement
R_O	the resistance force of the landside plate
q	the normal contact pressure
V	the tractor speed
x_c, y_c	the coordinates of the unit's center of mass
x_k,y_k	the coordinates of point of applying the resulting resistance force P of the plow relative to the tractor's center of mass
x_i,y_i	the coordinates of the instantaneous sliding center

Greek symbols

α	is tractor lateral tilt angle
β	the tilt angle of the resistance force to the longitudinal axis of the tractor
ρ	the radius of the trajectory curvature[m]
λ	is the empirical coefficient characterizing the elastic properties of the ground
μ	the coefficient of friction in the contact with

	the ground
μ_m	the maximum coefficient of frictionin the contact with the ground
μ_x,μ_y	the coefficient of friction in the longitudinal and transverse directions
γ,η	the present coordinates of the contact points

СТАБИЛНОСТ СМЕРА КРЕТАЊА ПОЉОПРИВРЕДНОГ ТРАКТОРА

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Несклад између ширине плуга и ширине трактора доводи до асиметричности агрегата за орање. Геометрија површине раоника код раоног плуга доприноси стварању латералних сила на оруђу. Све то доводи до неравнотеже оруђа и одступања трактора од праволинијског кретања за време орања. Да би одржавао праволинијско кретање трактора, возач трактора мора да прилагођава машину сваких 5-10 метара, што је веома напорно. Да бисмо истражили узроке латералног клизања трактора, конструисали смо математички модел који се састоји од једначина контролисаног кретања и једначина неконтролисаног смицања трактора под дејством спољашњих сила које дејствују на плуг. Опис интеракције дејства сила између погона и подлоге заснован је на теорији трења, при чему су узети у обзир анизотропија и еластична својства контакта.

На основу модела пасивног смицања контруисали смо ходограм максималне силе смицања код трактора на страни оруђа. Утврдили смо да сила смицања достиже максималну вредност трења само у случају транслаторног смицања када нападна линија пролази кроз тежиште трактора. У свим осталим случајевима сила мањег интензитета је узрок клизања трактора. Карактеристике и претпоставке модела су формулисане применом на трактору гусеничару и точкашу. Утврђено је да без обзира на латерални померај раоника код отпорности на вучу трактор клизи према поораном пољу. Резултат нумеричког експеримента показује да је главни узрок клизања агрегата трактора точкаша разлика у земљишту дуж обе стране трактора а не одступање раоника код отпорности на вучу.