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THEORY OF MOTION CONTROLLABILITY OF A WHEEL MACHINE-TRACTOR AGGREGATE

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Aim. To obtain analytically new dependencies, determining the indicator of motion controllability of a wheel machine-tractor aggregate, taking into consideration external forces, constructive and kinematic parameters of the aggregate while the latter moves in the transport mode. **Methods.** The methods of tractor and vehicle theories, theoretical mechanics, the theory of dynamic stability, and methods of numeric computer calculations. **Results.** A new theory of motion controllability of a wheel machine-tractor aggregate during its non-linear motion along the surface of the soil at an angle to the horizontal was elaborated. The analytic expressions for the determination of the actual indicator of aggregate controllability, including force and constructive parameters of a machine-tractor aggregate, affecting this indicator in the longitudinal-vertical plane were made. The analytic expressions were obtained for the transport mode of the aggregate movement. The conditions, in which cross slips of the directive wheels of the tractor with implements in the longitudinal plane were analytically considered for the first time. The analytic expressions for the determination of the required indicator of the controllability of the machine-tractor aggregate in the longitudinal plane, excluding any possibility of a cross slip of the aggregate while turning its directive wheels at a certain angle, were defined. **Conclusions.** Computer calculations demonstrated that during the non-linear movement along the surface of the soil at an angle of 12° to the horizontal the wheel machine-tractor aggregate will be controllable only if the wheel turning angles for the tractor with implements do not exceed 9°. In case of the working motion of this aggregate along the slope, its controllability is preserved on condition that the turning angle of directive wheels does not exceed 11°. It was established that the controllability of the wheel machine-tractor aggregate is determined by the actual λ_d and required λ_o indicators of controllability, which take into consideration the values of the vertical load on the directive wheels of the power source, the possibility of their turn in the longitudinal plane, and the pull during the deviation from rectilinear motion when it moves along the surface at an angle to the horizontal.

Keywords: wheel tractor, machine aggregate, power scheme, controllability indicator, equilibrium equations.
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INTRODUCTION

The controllability of the motion of machine-tractor aggregates, based on wheel power sources, is one of the main indicators of their performance. Recent analytic considerations of this issue have yielded several variants of solving this complicated technical task. However, in the prevailing majority of cases, the controllability of the two-dimensional motion of wheel machine-tractor aggregates is estimated using the indicator λ_d, used to determine the limits of vertical load on its front steer wheels, if they have a sufficiently stable contact with the soil surface and ensure the required motion controllability. Here there is a dependence, with which the vertical load on the directive wheels of the tractor with implements should have the value, equal at least 0.2 from its operating weight, *i.e.* $\lambda_d \geq 0.2$.

It is absolutely obvious that this estimation indicator takes into consideration the state of the conditional equilibrium of the machine-tractor aggregate during its motion in the longitudinal-vertical plane only. In conditions of actual exploitation a modern machine-tractor aggregate can both move on the slopes at an angle $\alpha \geq 12^o$, and have rather sufficient stability in the diametral plane. One should also consider a significantly increased translational velocity of modern machine-tractor aggregates, and the fact that it requires the directive wheel turns at the angles of β and the presence of angles δ of the pull of its tires.

On the other hand, while estimating the equilibrium conditions of the machine-tractor aggregate in the longitudinal-vertical plane without any consideration of parameters α, β, and δ, then theoretically, the condition $\lambda_d \geq 0.2$ may be quite achievable by mere re-distribution of weight, i.e. by ballasting (putting on some ballast weight) on its front directive wheels. However, in actual exploitation conditions (with angles α, β, and δ), this condition may seem unachievable, due to which some machine-tractor aggregate may prove to be actually uncontrollable.

Since the angle parameters α, β, and δ have a considerable effect on motion parameters and the controllability indicator for the wheel machine-tractor aggregate, there is a need for determining the analytic dependence, reflecting the degree of the impact of these parameters.

The study of the controllability of the motion of a wheel tractor while implementing different agricultural machines is dedicated many publications with detailed analysis of its equilibrium conditions in the longitudinal-vertical plane [1–3].

The works [4−8] suggest the abovementioned indicator λ_d as a criterion of controllability, but the equations of the motion of the machine-tractor aggregate along the slope in the longitudinal-vertical plane, considered therein, do not take into account the turns of steer wheels of the tractor with implements or the angles of the pull of the tires of its steer wheels.

The dynamics of the motion of machine-tractor aggregates with the consideration of angles α and β was studied by many researchers [6−9]. The equations obtained did not consider the impact of the re-distribution of forces, acting on the front and back axles of a wheel tractor in the longitudinal-vertical plane. The study of the two-dimensional motion of machine-tractor aggregates along the slope is dedicated the works [9−12], but they do not consider the criteria of motion stability, similar to the criterion λ_d or any other criteria.

The aim of the current work is to obtain analytically new dependencies, determining the indicator of motion controllability of a wheel machine-tractor aggregate, taking into consideration external forces, constructive and kinematic parameters of the aggregate while the latter moves in the transport mode.

MATERIALS AND METHODS

The theoretical studies were conducted using the methods of tractor and vehicle theories, theoretical mechanics, the theory of dynamic stability, and methods of numeric computer calculations.

RESULTS AND DISCUSSION

To have theoretical studies, at first we shall use the equation for the determination of the controllability indicator for the machine-tractor aggregate λ_d in the following form:

$$\lambda_d = \frac{N_B}{G_t} \geqslant 0.2, \tag{1}$$

where N_B – vertical load on the directive wheels of a tractor; G_t – operating force of the weight of the tractor.

However, in some circumstances the condition (1) may turn out to be insufficient to provide for satisfactory controllability of machine-tractor aggregates. It is especially relevant in case of their non-linear motion along the surface at some angle to the horizontal. Here the non-linearity of the aggregate motion results from the reaction of the tractor with implements on the steering impact – the turning angle of its steer wheels β.

Let us have analytic consideration of the transport motion of the plowing machine-tractor aggregate in the combination of a wheel tractor with implements, class 1.4, and the three-furrow plough, assembled at the back of it (in the upright position). Let us elaborate the equivalent scheme in the longitudinal-vertical plane, using the known methods of the theory of tractor and vehicle. According to this scheme, the machine-tractor aggregate has its transport non-linear motion upwards along the surface of the soil at the angle α (Fig. 1) to the horizontal. To simplify the analytic research in the first approximation, let us think that the contacts, which the steer wheels of the tractor with implements have with the soil, occur in points A and B. To compose the required equations of equilibrium of the considered mechanic system in the longitudinal-vertical plane, let

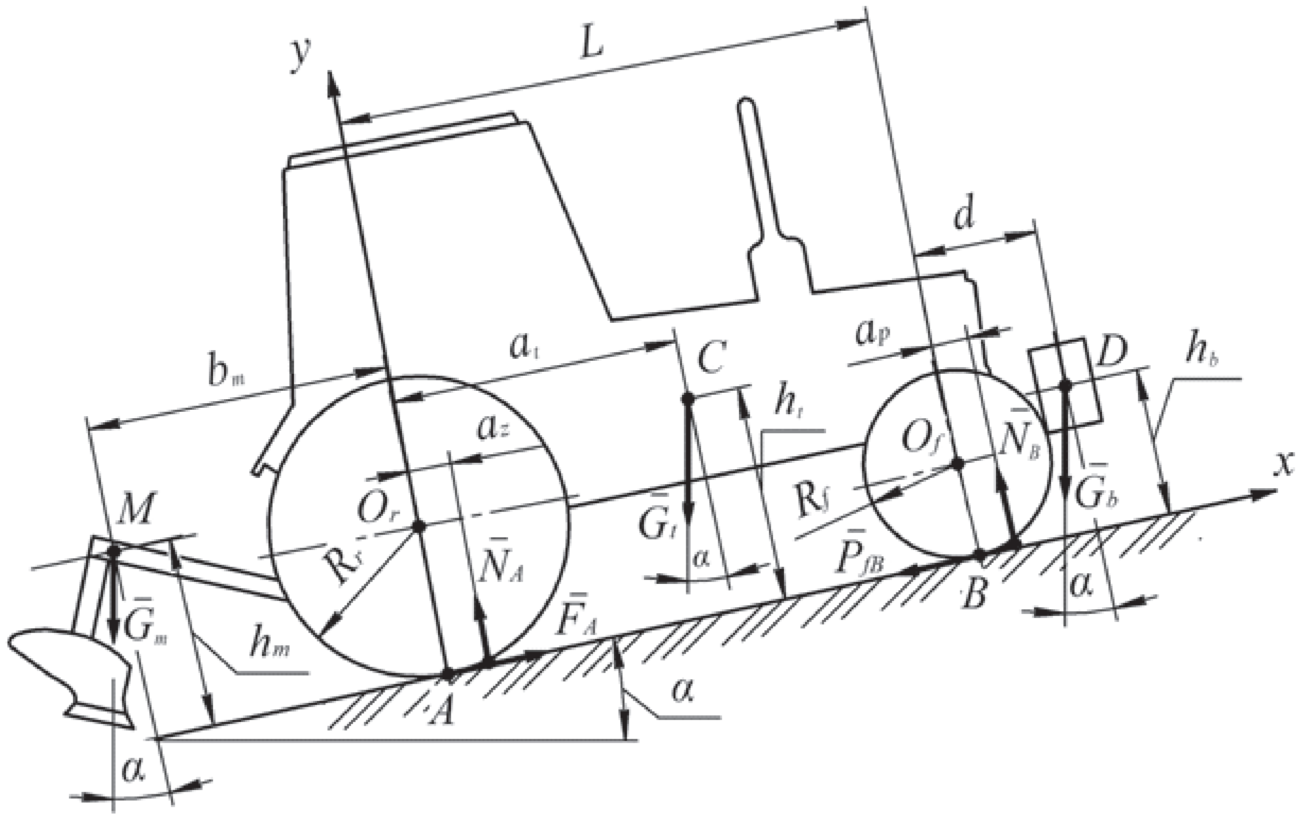

Fig. 1. The scheme of the forces, acting on the wheel machine-tractor aggregate during its transport motion upwards

us choose the flat Cartesian coordinate system xAy with the origin of coordinates in the point A of the contact of back wheels of the tractor and the soil. The X-axis Ax will be directed along-track of the aggregate, and the Y-axis Ay − upwards, *i.e.* perpendicularly to the direction of the aggregate motion. Therefore, the axis Ax is also at the angle of α to the horizontal.

The mentioned motion of the aggregate occurs only under the impact of the moving force of the back wheels of the tractor $\overline{F_A}$, applied in the point A. The drive mechanism of the tractor front axle is switched off, and the floating resistance force $\overline{P_{fB}}$, applied in the point B, acts on its steer wheels. The force of the tractor weight $\overline{G_t}$ is applied in the center of the tractor weights (point C with coordinates a_t, h_t). In addition, normal reactions of the soil to the steer wheels of the tractor are shifted some distance off the points of its wheel tires contacting the soil: by a_z from the point A the reaction $\overline{N_A}$ is shifted along-track of the aggregate, and by a_p from the point B the reaction $\overline{N_B}$ is also shifted in the direction of the motion (Fig. 1).

The impact of the plough on the wheel tractor is represented by the force of the weight of the ploughing device $\overline{G_m}$, concentrated in the point M with the coordinates b_m and h_m and shifted from the axis Ay by the angle of α. It is noteworthy that the construction of the power source (a wheel tractor) envisages the ballasting of its front axle with the force of the weight $\overline{G_b}$, concentrated in the point D with the coordinates (L + + d) and h_b (Fig. 1).

Only two forces from the ones, affecting the mentioned machine-tractor aggregate, are unknown: normal reactions on the front $\overline{N_B}$ and back $\overline{N_A}$ axles of the tractor. Finding them requires the elaboration of a system, consisting of two equations of aggregate equilibrium in the form of equal-zero sum of projections of all the forces on the axle Ay and the sum of the moments of all the forces regarding the point A, namely:

$$\left.\begin{aligned}&(G_t + G_b + G_m)\cos\alpha - N_B - N_A = 0,\\&G_t(a_t\cos\alpha - h_t\sin\alpha) - G_m(b_m\cos\alpha + h_m\sin\alpha) +\\&+ G_b[(L + d)\cos\alpha - h_b\sin\alpha)] - N_A a_z - N_B(L + a_p) = 0,\end{aligned}\right\} \quad (2)$$

where L – longitudinal basis of the tractor; a_p, a_z – action baselines of reactions $\overline{N_B}$ and $\overline{N_A}$.

Let us introduce the following legend:

$$\begin{aligned}K_1 &= G_t(a_t\cos\alpha - h_t\sin\alpha),\\K_2 &= G_m(b_m\cos\alpha + h_m\sin\alpha),\\K_3 &= G_b[(L + d)\cos\alpha - h_b\sin\alpha].\end{aligned} \quad (3)$$

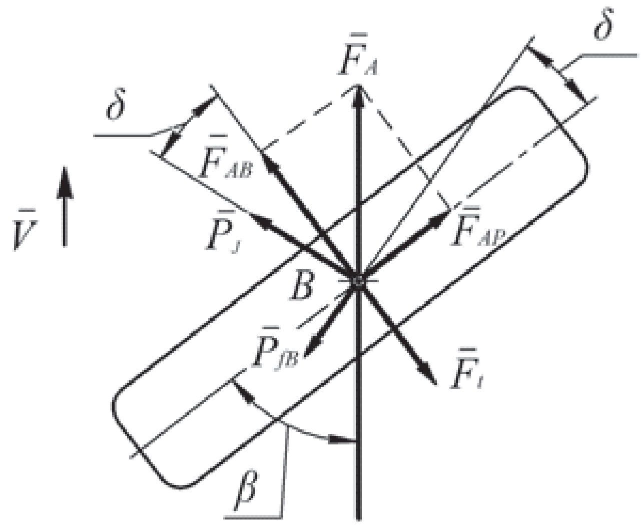

Fig. 2. The scheme of forces, affecting the front "equivalent" wheel of the tractor in case of the turning angle β in the horizontal plane during the transport motion of the ploughing machine-tractor aggregate

Then after the value substitution (3) in the system of equations (2) it gets the form:

$$\left.\begin{aligned}&(G_t + G_b + G_m)\cos\alpha - N_B - N_A = 0,\\ &K_1 - K_2 + K_3 - N_A a_z - N_B (L + a_p) = 0.\end{aligned}\right\} \quad (4)$$

The system of equations (4) yields the value of the reaction N_B:

$$N_B = \frac{K_1 - K_2 + K_3 - a_z(G_t + G_b + G_m)\cos\alpha}{L - a_z - a_p}. \quad (5)$$

It is known from the theory of tractor [1] that

$$\begin{aligned}a_p &= f_k R_f,\\ a_p &= f_k R_r,\end{aligned} \quad (6)$$

where f_k – coefficient of floating resistance; R_f, R_r – radii of floating for front and back wheels of the tractor.

Taking into consideration (6), the equation (5) transforms into the equation of the following kind:

$$N_B = \frac{K_1 - K_2 + K_3 - f_k R_r(G_t + G_b + G_m)\cos\alpha}{L - f_k(R_r - R_f)}. \quad (7)$$

Taking into consideration (1) and (7), the equation for the determination of the controllability indicator λ_d has the following final form:

$$\lambda_d = \frac{K_1 - K_2 + K_3 - f_k R_r(G_t + G_b + G_m)cos\alpha}{G_t[L - f_k(R_r - R_f)]}. \quad (8)$$

It follows from the equation (8) that the fulfillment of the condition (1) depends on many factors. The latter are both force ($\overline{G_t}$, $\overline{G_m}$, $\overline{G_b}$) and constructive (a_t, b_m, d, h_t, h_m, h_b, L, R_r, R_f) parameters of the machine-tractor aggregate, and the conditions of its motion (angle α, coefficient f_k). However, all of them affect the indicator λ_d only in the longitudinal-vertical plane. At the same time, during the non-linear motion of the machine-tractor aggregate at a certain value of the reaction $\overline{N_B}$ (and thus, of the indicator λ_d) there may be such unloading of the steer wheels of the tractor, which will condition their cross slip in the horizontal plane. Both the controllability and total stability of the aggregate motion will decrease as a result. In some conditions the machine-tractor aggregate may become uncontrolled at all.

Let us present the front wheels of the tractor as one "equivalent" wheel [10–12], located in the plane, passing through the longitudinal axle of the tractor symmetry, for our following theoretical analysis (Fig. 2).

It has already been stated that the front axle of the tractor, on the side of the tractor frame, is affected by the moving force $\overline{F_A}$. It follows from the equilibrium equation, written in the form of equal-zero sum of projections of all the forces on the axle Ax (Fig. 1), that by the module this force will equal:

$$F_A = (G_t + G_b + G_m)\sin\alpha + f_k N_B. \quad (9)$$

It should be also noted that in the horizontal plane the projection of the force $\overline{P_{fB}}$, applied in the point B, is shifted from the longitudinal axle of the symmetry of the front "equivalent" wheel at the angle of the tire pull δ. In this case it is determined by the following equation:

$$P_{fB} = f_k N_B. \quad (10)$$

Taking this fact into consideration, we use (9) and (10) to obtain the value of the force F_A:

$$F_A = (G_t + G_b + G_m)\sin\alpha + f_k N_B. \quad (11)$$

In case of a steering impact – the directive wheel turning angle β – the longitudinal constituent $\overline{F_{AP}}$ of the force $\overline{F_A}$ pushes the "equivalent" wheel along-track, and the cross constituent $\overline{F_{AB}}$, along with the inertial force of the front axle $\overline{P_J}$, tries to dislocate it to the side (Fig. 2).

The impact of all the side forces from the soil on the «equivalent» wheel results in the reaction of friction $\overline{F_t}$. As follows from the scheme of forces, presented in Fig. 2, the condition of this wheel motion without any cross slip is expressed by the following inequality:

$$F_t \geq F_{AB} - P_{fB}\sin\delta + P_J\cos\delta. \quad (12)$$

The friction reaction $\overline{F_t}$ depends on the friction coefficient for the "equivalent" wheel and the soil f_t and the value of the vertical load on the directive wheels of the tractor $\overline{N_B}$. Thus, its value will equal:

$$F_t = f_t N_B. \qquad (13)$$

It also follows from the analysis of the data for the force scheme (Fig. 2) that the force F_{AB} will equal:

$$F_{AB} = F_A \sin\beta. \qquad (14)$$

The inertial force of the front axle of the tractor will be defined by the expression:

$$P_J = \frac{N_B V^2}{gP_B}, \qquad (15)$$

where V – the velocity of the transposition of the point B (Fig. 2), which, with a sufficient degree of accuracy, may be deemed to be equal the velocity of the motion of the machine-tractor aggregate; g – free-falling acceleration; R_B – turn radius of the front axle of the tractor. According to [13], its value will equal:

$$R_B = \frac{L}{\sin(\beta + \delta)}. \qquad (16)$$

After putting (16) in (15), we have:

$$P_J = \frac{N_B V^2 \sin(\beta + \delta)}{Lg}. \qquad (17)$$

Taking into consideration (11), (13), (14), and (17), the equation (12) gets the following form:

$$f_t N_B \geqslant \Big[\frac{(G_t + G_b + G_m)\sin\alpha\sin\beta + f_k N_B \sin\beta - f_k N_B \sin\delta}{Lg} + \frac{N_B V^2 \sin(\beta + \delta)}{Lg}\Big]. \qquad (18)$$

Working with the inequality (18) regarding N_B, we obtain the following value, in case of which this “equivalent” wheel moves without any cross slip:

$$N_B \geqslant \frac{gL(G_t + G_b + G_m)\sin\alpha\sin\beta}{Lg[f_t - f_k(\sin\beta - \sin\delta)] - V^2 \sin(\beta + \delta)\cos\delta}. \qquad (19)$$

Having divided both parts of the inequality (19) by the force of the tractor weight G_t, we will actually obtain the value λ_o:

$$\lambda_o = \frac{N_B}{G_t} \geqslant \frac{gL(G_t + G_b + G_m)\sin\alpha\sin\beta}{\{Lg[f_t - f_k(\sin\beta - \sin\delta)] - V^2 \sin(\beta + \delta)\cos\delta\}\, G_t}. \qquad (20)$$

Thus, the equation (8) presents the actual value of the aggregate controllability λ_d, and the dependence (20) defines its required value λ_d. Here the satisfactory controllability of the motion of the machine-tractor aggregate will occur only in case of compliance with the following condition:

$$0 < \lambda_d \geq \lambda_o. \qquad (21)$$

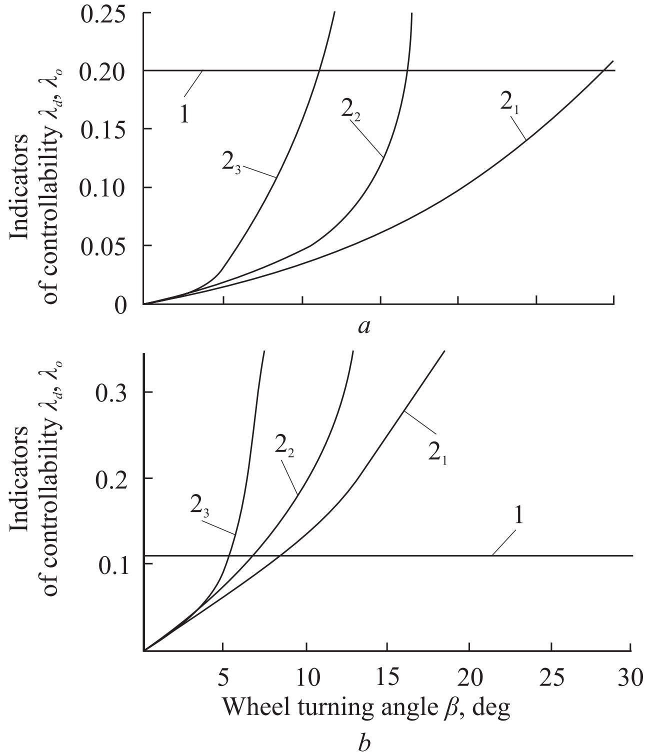

Fig. 3. The dependences of the actual λ_d (curves 1) and required λ_o (curves 2) values of the controllability of the transport machine-tractor aggregate on the wheel turning angles β of the directive tractor wheels with the angle α of the slopes of the road surface $\alpha = 0^{\circ}$ (*a*); $\alpha = 12^{\circ}$ (*b*) and the velocity of the translational movement: 2_1 – V = 3.5 m/s; 2_2 – V = = 5.0 m/s; 2_3 – V = 7.0 m/s

Let us consider how conditions (1) and (21) are fulfilled for the machine-tractor aggregate under study, moving in the transport mode. Here numerous computer calculations are made with the following values of its initial constructive and kinematic parameters: G_t = 40 kN; G_b = 0; L = 2.45 m; a_t = 0.82 m; h_t = 0.9 m; G_m = 4.5 kN; b_m = 2.2 m; h_m = 1.25 m; R_r = 0.73 m; R_f = 0.46 m; d = 0.7 m; h_b = 1.0 m; f_k = 0.12; $\beta = 0…30^{\circ}$; $\delta = 0.01\cdot\beta$; V = 3…7 m/s.

The results of numerous computer calculations in the composed program were used to compose the charts, where the dependences of controllability indicators for the machine-tractor are presented (Fig. 3).

The calculations demonstrated that in some cases this machine-tractor aggregate will be controllable even with its non-linear motion along the road with-

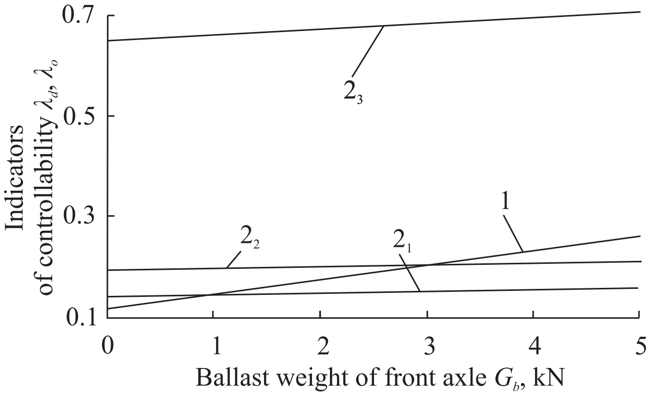

Fig. 4. The dependencies of the actual λ_d (curve 1) and required λ_o (curves 2) values of the controllability indicators for the machine-tractor aggregate on the value of the ballasting on the front axle of the wheel tractor and the velocity of its movement: $a = 12^{\circ}$; $b = 10^{\circ}$; 2_1 – V = 3.5 m/s; 2_2 – V = = 5.0 m/s; 2_3 – V = 7.0 m/s

out any slope ($a = 0$) in the longitudinal-vertical plane.

Thus, with the velocity of the translational movement of $V = 3.5$ m/s and less, the controllability of the machine-tractor aggregate will be preserved in the whole range of the change in the turning angle b of the directive tractor wheels (curve 2_1, Fig. 3, *a*), as the condition (21) is fulfilled. At the same time, while moving with the velocity of 5 m/s (18 km/h), the machine-tractor aggregate will be controllable only if the value of the angle b does not exceed 16° (curve 2_2, Fig. 3, *a*). When the machine-tractor aggregate is moving with the velocity of 7 m/s (25.2 km/h), the condition (21) will not be violated, and the controllability will be preserved, if the value of the wheel turning angle b of the directive tractor wheels changes in the range of 0…11° (curve 2_3, Fig. 3, *a*).

In many countries the normative operation documents for tractors stipulate that the tractor in the composition of any machine-tractor aggregate should be able to have stable movement along the slopes of at least $\alpha = 12^{\circ}$. In case of the ploughing aggregate under study, the condition (1) for its linear movement is not fulfilled, as the actual value of the indicator $\lambda_d = 0.11$ (curve 1, Fig. 3, *b*) is lower than its normative value. However, the final conclusion on the controllability or uncontrollability of the machine-tractor aggregate may be drawn only after checking the condition (21). The calculations using the dependence (20) demonstrate that with the value of the directive wheel turning angle b not exceeding 8° and the velocity of its movement V £ 3.5 m/s the condition (21) is fulfilled (curve 2_1, Fig. 3, *b*) and thus this machine-tractor aggregate is controllable. Its controllability will be preserved at the velocity of 7 m/s, but in this case the wheel turning angle b should not exceed 5° (curve 2_3, Fig. 3, *b*).

One of the suggested ways to solve this technical problem is the ballasting of the front axle of the wheel tractor. The results of computer calculations were used to build graphic dependences of the values of the controllability indicators for the machine-tractor aggregate on the value of ballasting on the front axle of the tractor (Fig. 4). It was determined that the increase in the value of the parameter G_b leads to the increase in the load N_b on the directive wheels of the power source along with the indicator λ_d (curve 1, Fig. 4). The calculations demonstrated simultaneous increase in the required value of the controllability indicator, i.e. λ_o. But it is different for different velocities of the aggregate motion. The analysis of the data in Fig. 4 also demonstrates that at $a = 12^{\circ}$, $b = 10^{\circ}$ and $V = 3.5$ m/s the condition (21) may be fulfilled with the value of the ballast of $G_b \geq 1$ kN. Here the weight of the ballast will equal $G_b = 1.020$ kg.

If the aggregate moves with the velocity of 5 m/s, the equality of the actual λ_d (curve 1, Fig. 4) and required λ_o (curve 2_2) indicators of the controllability will take place at the value of the ballast of 3 kN (the ballast weight will equal $G_b = 3.060$ kg).

At the same time the condition (21) for the controllable (and thus stable) motion of the wheel machine-tractor aggregate under study with the velocity of 7 m/s (25.2 km/h) will be possible for the ballasting of the front axle of the tractor of $G_b = 33$ kN (ballast weight will equal $G_b = 3.364$ kg). It is quite evident that it is practically unrealistic to place such a ballast weight on the front axle of a wheel tractor of 1.4 drawbar category.

Therefore, the application of ballasts on the front axle of the directive wheels on any wheel power source may solve the problem of controllability of non-linear motion of the machine-tractor aggregate only for a specific range of velocities.

CONCLUSIONS

The analysis of the controllability of the machine-tractor aggregate should involve the indicator, taking into consideration both the value of the vertical load on the directive wheels of the power source and the possibility of their turning and the pull in case of the machine-tractor aggregate diverting from its linear motion and its transposition at an angle to the horizontal.

There is an obtained analytical expression to determine the controllability indicator for the machine-tractor aggregate, which conditions its required value λ_o and considers the interrelation both with force and constructive parameters of the machine-tractor aggregate, and with the conditions of its motion.

The controllability of the machine-tractor aggregate may be considered sufficient, if the actual (calculated by the formula (8)) and required (calculated by the formula (20)) values of the controllability indicator for the aggregate meet the condition, defined by the equation (21).

Теорія керованості руху колісного машинно-тракторного агрегата

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Мета. Отримати аналітично нові залежності, що визначають показник керованості руху колісного машинно-тракторного агрегату, який враховує зовнішні сили, конструктивні і кінематичні параметри агрегату при його русі в транспортному режимі. **Методи.** Методи теорії трактора і автомобіля, теоретичної механіки, теорії стійкості руху, а також методи чисельних розрахунків на ЕОМ. **Результати.** Розроблено нову теорію керованості руху колісного машинно-тракторного агрегату при його непрямолінійному русі по поверхні грунту, нахиленій під кутом до горизонту. Складено аналітичні вирази для визначення дійсного показника керованості агрегату, що включають силові і конструктивні параметри машинно-тракторного агрегату, які впливають на цей показник в поздовжньо-вертикальній площині. Аналітичні вирази отримано для транспортного режиму руху агрегату. Вперше аналітично розглянуто умови, за яких можуть виникнути поперечні ковзання керованих коліс агрегатуючого трактора в горизонтальній площині. Насамкінець виписано аналітичні вирази для визначення необхідного показника керованості машинно-тракторного агрегату в горизонтальній площині, що виключають можливість бічного ковзання агрегату при повороті його керованих коліс на певний кут. **Висновки.** В результаті проведених на ЕОМ розрахунків встановлено, що за непрямолінійного руху по поверхні грунту, нахиленій до горизонту під кутом 12 °, колісний машинно-тракторний агрегат буде керованим лише тоді, якщо величина кутів повороту керованих коліс його агрегатуючого трактора не перевищить 9 °. При робочому русі даного агрегату по похилій ділянці його керованість зберігається за умови, якщо кут повороту керованих коліс трактора не перевищує 11 °. З'ясовано, що керованість колісного машинно-тракторного агрегату визначається дійсним λ_d і необхідним λ_o показниками керованості, які враховують величини вертикального навантаження на керованих колесах енергетичного засобу, можливість їхнього повороту в горизонтальній площині, а також відведення при відхиленні машинно-тракторного агрегату від прямолінійного напряму при його русі по поверхні, нахиленій під кутом до горизонту.

Ключові слова: колісний трактор, машинний агрегат, силова схема, показник керованості, рівняння рівноваги.

Теория управляемости движения колесного машинно-тракторного агрегата

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Цель. Получить аналитически новые зависимости, определяющие показатель управляемости движения колесного машинно-тракторного агрегата, учитывающий внешние силы, конструктивные и кинематические параметры агрегата при его движении в транспортном режиме. **Методы.** Методы теории трактора и автомобиля, теоретической механики, теории устойчивости движения, а также методы численных расчетов на ЭВМ. **Результаты.** Разработана новая теория управляемости движения колесного машинно-тракторного агрегата при его непрямолинейном движении по поверхности почвы, наклоненной под углом к горизонту. Составлены аналитические выражения для определения действительного показателя управляемости агрегата, включающие силовые и конструктивные параметры машинно-тракторного аг-

регата, которые влияют на этот показатель в продольно-вертикальной плоскости. Аналитические выражения получены для транспортного режима движения агрегата. Впервые аналитически рассмотрены условия, при которых могут возникнуть поперечные скольжения управляемых колес агрегатирующего трактора в горизонтальной плоскости. В итоге выписаны аналитические выражения для определения требуемого показателя управляемости машинно-тракторного агрегата в горизонтальной плоскости, исключающие возможность бокового скольжения агрегата при повороте его управляемых колес на определенный угол. **Выводы.** В результате проведенных на ЭВМ расчетов установлено, что при непрямолинейном движении по поверхности почвы, наклоненной к горизонту под углом 12 °, колесный машинно-тракторный агрегат будет управляем только тогда, когда величины углов поворота управляемых колес его агрегатирующего трактора не превысят 9 °. При рабочем движении данного агрегата по наклонному участку его управляемость сохраняется при условии, если угол поворота управляемых колес трактора не превышает 11 °. Установлено, что управляемость колесного машинно-тракторного агрегата определяется действительным λ_d и требуемым λ_o показателями управляемости, которые учитывают величины вертикальной нагрузки на управляемых колесах энергетического средства, возможность их поворота в горизонтальной плоскости, а также увод при отклонении машинно-тракторного агрегата от прямолинейного направления при его движении по поверхности, наклоненной под углом к горизонту.

Ключевые слова: колесный трактор, машинный агрегат, силовая схема, показатель управляемости, уравнения равновесия.

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