THEORETICAL INVESTIGATION OF TURNING ABILITY OF TWO-MACHINE SOWING AGGREGATE

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Abstract. It is purposeful to increase the efficiency of the 80-100 hp tractors (traction class 1.4) in sowing agricultural crops by increasing the working width of the technological part, using wide-span sowing machine-and-tractor aggregates. However, their movement characteristics on the turning strips in many respects determine their technical and economic performance, as a whole. It has been found out by the conducted research that a motivated choice of the parameters of wide-span sowing machine-and-tractor aggregates allows them making manoeuvres of turns on the turning strip in an optimal mode, which promotes reducing the length and time for turns by 4.5-11.2 % and the width of the turning strip by 4.9-12.1 %. In order to improve the turning ability of a two-machine sowing aggregate, it is desirable to apply ballasting (i.e., installation of additional loading) of the front axle wheels of the tractor. Thus, additional loads with a mass of 180 kg, installed on it, can reduce the turning radius of the aggregate. The most noticeable result of ballasting is achieved, when the turning angle of the driven wheels of the tractor is greater than 0.32 rad. At the maximum value of the control action (α = 0.5 rad) the reduction in the turning radius of the aggregate, due to ballasting the front axle of the tractor, is 0.8 m (i.e. 15 %). It has been theoretically established that, in case the speed of the movement is increased from 1.0 to 3.0 $m \cdot s^{-1}$, the turning radius of the unit tends to decrease. Such a result is because the increase in the drift angle of the rear wheels of the tractor outstrips the increase in the drift angle of the tires of its front wheels.

Keywords: tractor, machine, sowing, turning radius.

Introduction

Efficient production management in the agricultural sector needs such material and technical resources that are capable to ensure fulfilment of the entire amount of mechanised operations in optimal time with a high quality and low costs [1]. One of the ways to solve such a problem is the use of high-performance wide-span machine-and-tractor aggregates, particularly, for sowing [2].

It is purposeful to increase the efficiency of machine-and-tractor aggregates in sowing agricultural crops by increasing the working width of the aggregate, using two trailed grain seeders instead of one [3]. A certain problem for assembling such trailed seeders as SZ-3.6 seeders is because of the external arrangement of their wheels. For this reason it is impossible to complete them as part of an aggregate in a single row. It is expedient to carry out efficient aggregation of these sowing machines by means of the new semi-mounted coupling developed by us [3]. The potential advantages of a semi-mounted coupling create prerequisites for theoretical studies aimed at the improvement of the technical and economic indicators of a high-performance wide-span sowing aggregate based on a tractor, traction class 1.4, by justifying its design and kinematic parameters.

At the same time it is proved by practice that for each type of turning of the machine-and-tractor aggregate there is an optimal radius, at which the length of the manoeuvre will be the shortest. The optimum turning radius can be achieved by moving on the turning strip in the optimal mode, determined by its design and kinematic parameters [5]. Execution of the turning manoeuvre of the machine-and-tractor aggregate in an optimal mode helps reduce the length and time of turns by 4.5-11.2 %, and the width of the turning strip by 4.9-12.1 % [6].

A great number of scientific studies have been devoted to the issue of the turning ability of agricultural machine-and-tractor aggregates. At the same time, a significant part of these studies is devoted to studying the issue concerning the aggregates based on a tractor with an articulated frame [7]. In this connection, the dependencies obtained by scientists cannot practically be used by us to analyse the turning ability of a machine-and-tractor aggregate based on an energy source of the classical layout. The reason lies in the fundamental difference in the kinematic turning scheme of these tractors. In addition, most of the issues concerning the turning ability were discussed for machine-and-tractor aggregates, in which the technological part was not physically presented, but was reflected by its impact upon the tractor through the draught resistance force and the turning angle in a horizontal plane [8].

Many scientists are of the opinion that the determining evaluative parameters of a machine-and-tractor aggregate are the minimum radius and the turning time. However, the results that they obtained are ambiguous. Thus, in [9; 10] it is emphasised that, increasing the turning speed, the manoeuvring time for the aggregate decreases. However, in [9] a completely different regularity is established. With the manoeuvring speed of the machine-and-tractor aggregate increasing, the time for its execution first decreases to a certain value and then it begins to grow.

Much less attention was paid to the study of the turning dynamics of the machine-and-tractor aggregates. In such a situation it is not possible to make a justified choice of structural and other characteristics of high-performance sowing machine-and-tractor aggregates. Quite often this is due to the fact that in the obtained analytical dependencies, describing the discussed process of the movement of the aggregate on the turning strip, the parameters of its technological part are not presented. And, if their choice is not justified, the tractor may not realise its own turning ability in the aggregate with these or other agricultural machines. Moreover, there may be a movement of the machine-and-tractor aggregate with an unjustified large radius or turning time. At the same time, through studies [11] it has been established that making the turning manoeuvre of the aggregate in the optimal mode helps reduce the length and time of turns by 4.5-11.2 %, and the width of the turning strip by 4.9-12.1 %.

At the same time, studies have established that making the manoeuvre of turning the aggregate in the optimal mode helps reduce the length and time for turns by 4.5-11.2 %, and the width of the turning strip by 4.9-12.1 %. The aim of this research is theoretical studies of the turning ability of a wide-span two-machine sowing machine-and-tractor aggregate depending on its design and kinematic parameters.

Materials and methods

The research methods are based on the foundations of theoretical mechanics, tractor theory, as well as programming and numerical calculations on a PC. In order to solve this task, we will consider a sowing machine-and-tractor aggregate consisting of two SZ-3.6 seeders and a tractor of the classical arrangement, traction class 1.4 (Fig. 1) with one rear driving axle [3].

Fig. 1. **Experimental two-machine sowing aggregate moving on turn**

When moving on the turn, a number of corresponding forces act upon the aggregate to be studied (see Fig. 1). Let us construct a scheme, equivalent to the turning conditions of this aggregate (Fig. 2). In this scheme we will present the frontal driven wheels of the aggregating wheeled tractor as one equivalent wheel, assuming that both driven wheels of a real aggregating tractor are under approximately the same conditions. We consider that during the turn the frontal driven equivalent wheel, the centre of which is located at point B, is turned by the angle α in the direction of the turn. The longitudinal base of the tractor is marked as AB. In the centre of the middle of the axle of the driving wheels of the tractor, i.e. at point A, a coupling of a new design is attached, in which the actions of the attached seeders are characterised by forces P_{f1} and P_{f2}, that is, when moving on the turning strip, the impact of the technological part of the aggregate upon the aggregating tractor is represented by the resistance forces to rolling of the trailed seeders P_{f1} and P_{f2} that deviate from the rectilinear direction of the movement by angles φ_1 and φ_2.

Let us show the forces acting upon this aggregate. First of all, this is the driving force F_a of the rear driving wheels and the resistance forces to rolling P_{fb} of the frontal driven wheels of the tractor, applied at points A and B of the centres of the corresponding axles (Fig. 2). At these points we will also concentrate the centrifugal forces of inertia P_{ja} and P_{jb}, as well as the lateral forces T_a and T_b. Under the impact of external forces, the frontal driven and the rear driving wheels of the aggregating tractor are rolled with a drift of the tires, the angles of which are indicated for the front axle as δ_b, and for the rear axle as δ_a. Consequently, the driving force F_a of the rear wheels and the resistance force to rolling P_{fb} of the frontal driven wheels deviate by the respective angles δ_a and δ_b of the tires. The linear dimensions that determine the configuration of the particular dynamic system are clear from the equivalent scheme (Fig. 2). In the equivalent scheme we designate the speed of the frontal driven axle of the aggregating tractor as V_b and that of the rear driving axle as V_a, showing them in the form of vectors applied at points A and B. Besides, the vectors of these speeds are also deviated by respective angles δ_a and δ_b of the tire drifts. Regarding the movement on the turn only in a horizontal plane, we introduce a planar rectangular Cartesian coordinate system XAY in which the centre is located at point A, and axis AY passes through the longitudinal axis of the aggregating tractor.

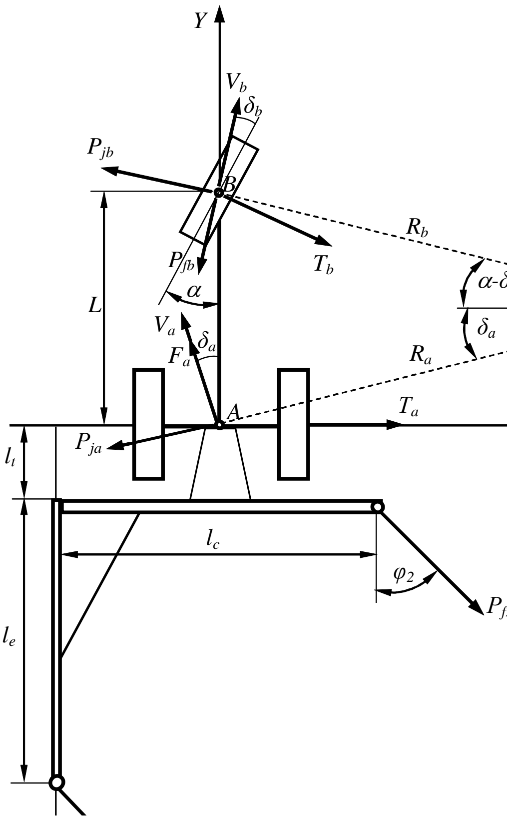

Fig. 2. **Equivalent turning scheme of two-machine sowing aggregate**

The instantaneous turning centre (point O_t) of this aggregate is located at the intersection of the perpendiculars drawn through the points A and B to the velocity vectors V_a and V_b. However, because of the phenomenon of the tire wear the instantaneous turning centre O_t of the aggregate is displaced in the longitudinal direction by value Y_a (see Fig. 2). In order to determine the turning radius R_a and the displacement Y_a of the instantaneous turning centre, it is sufficient to compile a system of equilibrium equations for the particular aggregate in a plane. At the first approximation, excluding from the system of algebraic equations of the body equilibrium in the plane one of their equations, for example, the algebraic sum of the projections of all forces on axis X, we obtain:

$$\left.\begin{aligned}\sum_{k=1}^{n}\left(F_k\right)_y=0,\\ \sum_{k=1}^{n}M_A\left(F_k\right)=0.\end{aligned}\right\}, \tag{1}$$

Taking into account the forces acting upon this aggregate, as well as the smallness of the drift angles δ_a and δ_b of the tires of the tractor propelling wheels, the system of algebraic equations (1) takes the following form:

$$\left.\begin{aligned}&P_{jb}\left(\sin\alpha-\delta_b\cos\alpha\right)-P_{fb}\left(\cos\alpha+\delta_b\sin\alpha\right)-T_b\sin\alpha+\\&+F_a-P_{ja}\delta_a-P_{f2}\cos\varphi_2-P_{f1}\cos\varphi_1=0,\\&LT_b\cos\alpha-LP_{jb}\left(\cos\alpha+\delta_b\sin\alpha\right)-LP_{fb}\left(\sin\alpha-\delta_b\cos\alpha\right)+\\&+P_{f2}\left(\frac{1}{2}l_c\cos\varphi_2-l_t\sin\varphi_2\right)-P_{f1}\left(l_t\sin\varphi_1+\frac{1}{2}l_c\cos\varphi_1\right)=0.\end{aligned}\right\}, \tag{2}$$

where L, l_c, l_t – parameters the nature of which is clear from Fig. 1.

The force of the rolling resistance P_{fb} of the frontal axle of the tractor is found from the following well-known expression:

$$P_{fb}=M_b\cdot f_k\cdot g\ , \tag{3}$$

where M_b – mass of the tractor on the frontal axle of the tractor, kg.
f_k – coefficient of rolling resistance of the tractor;
g – acceleration of gravity, m·s^{-2}.

The draught resistance of the SZ-3.6 seeders on the turning strip is practically the same and is determined as follows:

$$P_{f1}=P_{f2}=M_s\cdot f_k\cdot g\ , \tag{4}$$

where M_s – perating mass of the seed drill, kg.

The traction force F_a of the rear wheels of the tractor can be determined with sufficient for practice accuracy according to the following relationship:

$$F_a=P_{fb}+P_{f1}+P_{f2}\,. \tag{5}$$

The drift angles of the tractor tires, in accordance with Fig. 1 and taking into account their smallness, can be determined from such dependencies:

$$\begin{aligned}&\delta_a=K\cdot Y_a,\\&\delta_b=\frac{\tan\alpha-K\left(L-Y_a\right)}{1+K\cdot\tan\alpha\left(L-Y_a\right)},\end{aligned} \tag{6}$$

where $K = 1/R_a$ – turning curvature of the machine-and-tractor aggregate, m^{-1}.

When turning a machine-and-tractor aggregate, based on a wheeled tractor, with a relatively short longitudinal base, the difference between the linear speeds of the middle of its axles can be neglected, and it can be considered that:

$$V_a\approx V_b\approx V_t\,, \tag{7}$$

where V_t – speed of the movement of the aggregate on the turning strip, m·s^{-1},
V_a, V_b – linear speeds of the middle of the tractor axles, m·s^{-1}.

The angular turning speeds of the middle of the tractor axles can be determined in the following way:

$$\begin{aligned}&\omega_a=\frac{V_a}{R_a}-\dot{\delta}_a=V_t\cdot K-\dot{\delta}_a,\\&\omega_b=\frac{V_b}{R_a}-\dot{\delta}_b=V_t\cdot K-\dot{\delta}_b.\end{aligned} \tag{8}$$

Taking into account dependences (6), the lateral forces T_a and T_b can be expressed as follows:

$$T_a = k_a \delta_a = k_a K Y_a,$$
$$T_b = k_b \delta_b = \frac{k_b \left[\tan \alpha - K \left(L - Y_a \right) \right]}{1 + K \tan \alpha \left(L - Y_a \right)}, \tag{9}$$

where k_a and k_b – drift coefficients of the rear and frontal wheels of the tractor (N·rad^{-1}), determined according to the methodology described in [9].

Taking into consideration dependences (7) and (8), the centrifugal inertia forces can be expressed as:

$$P_{ja} = M_a V_a \omega_a = M_a V_t \left[K V_t - K \dot{Y}_a - \dot{K} Y_a \right],$$
$$P_{jb} = M_b V_b \omega_b = M_b V_t \left[K V_t - \frac{\left[K \dot{Y}_a + \dot{K} \left(Y_a - L \right) \right] \cdot \left(1 + \tan^2 \alpha \right)}{\left[1 + K \tan \alpha \left(L - Y_a \right) \right]^2} \right], \tag{10}$$

where M_a, M_b – masses of the tractor on the rear and frontal axles of the tractor, kg.

In order to determine the turning angles (φ_1 and φ_2) of the seeders, considering the drift of the tires of the wheels of the aggregating tractor, let us regard the scheme shown in Fig. 3.

From Fig. 3 it follows that:

$$\tan \varphi_1 = \frac{O_1 Y_1}{O_t O_1} = \frac{K \left[Y_a + l_t + l_e + \left(\dfrac{l_n}{\cos \varphi_1} \right) \right]}{1 + \dfrac{l_c}{2} K}, \tag{11}$$
$$\tan \varphi_2 = \frac{X_1 Y_2}{O_t X_1} = \frac{K \left[Y_a + l_t + \left(\dfrac{l_n}{\cos \varphi_2} \right) \right]}{1 - \dfrac{l_c}{2} K}.$$

where l_n – parameter the nature of which is clear from Fig. 3.

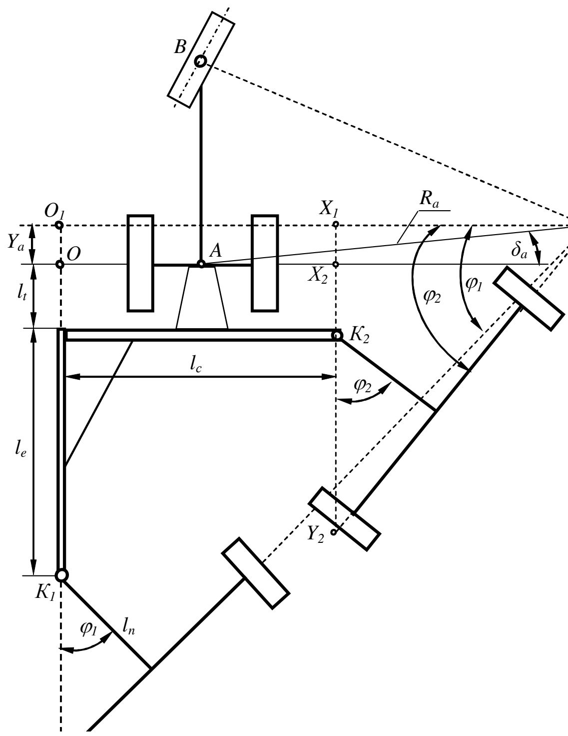

Fig. 3. **Scheme for determination of turning angles of trailed seeders**

Results and discussion

On the basis of the foregoing dependencies the resulting mathematical model of the turn of a high-performance two-machine sowing aggregate can be written in the form of the following system of equations:

$$\left.\begin{aligned}
&P_{jb}\left(\sin\alpha-\delta_b\cos\alpha\right)-P_{fb}\left(\cos\alpha+\delta_b\sin\alpha\right)-T_b\sin\alpha+F_a-\\
&-P_{ja}\delta_a-P_{f2}\cos\varphi_2-P_{f1}\cos\varphi_1=0,\\
&LT_b\cos\alpha-LP_{jb}\left(\cos\alpha+\delta_b\sin\alpha\right)-LP_{fb}\left(\sin\alpha-\delta_b\cos\alpha\right)+\\
&+P_{f2}\left(\frac{1}{2}l_c\cos\varphi_2-l_t\sin\varphi_2\right)-P_{f1}\left(l_t\sin\varphi_1+0.5l_c\cos\varphi_1\right)=0,\\
&P_{ja}=M_aV_t\left[K\cdot V_t-K\cdot\dot{Y}_a-\dot{K}\cdot Y_a\right],\\
&P_{jb}=M_bV_t\left[K\cdot V_t-\frac{\left[K\cdot\dot{Y}_a+\dot{K}\left(Y_a-L\right)\right]\left(1+\tan^2\alpha\right)}{\left[1+K\cdot\tan\alpha\left(L-Y_a\right)\right]^2}\right],\\
&T_a=k_a\delta_a=k_aK\cdot Y_a,\\
&T_b=k_b\delta_b=\frac{k_b\left[\tan\alpha-K\left(L-Y_a\right)\right]}{1+K\cdot\tan\alpha\left(L-Y_a\right)},\\
&\tan\varphi_1=\frac{K\left[Y_a+l_t+l_e+\left(\dfrac{l_n}{\cos\varphi_1}\right)\right]}{1+\dfrac{l_c}{2}K},\\
&\tan\varphi_2=\frac{X_1Y_2}{O_tX_1}=\frac{K\left[Y_a+l_t+\left(\dfrac{l_n}{\cos\varphi_2}\right)\right]}{1-\dfrac{l_c}{2}K},\\
&\delta_a=K\cdot Y_a,\\
&\delta_b=\frac{\tan\alpha-K\left(L-Y_a\right)}{1+K\cdot\tan\alpha\left(L-Y_a\right)}.
\end{aligned}\right\}\qquad(12)$$

In the obtained mathematical model (12) two parameters are unknown:

1. curvature of the path of the movement of the aggregate $K = 1/R_a$;
2. displacement coordinate of the turning centre Y_a.

The input parameters that specify the dynamics of the movement of the aggregate are:

- turning angle of the driven wheels of the tractor α;
- speed of the movement of the aggregate on the turning strip V_t.

As variable parameters of the mathematical model, the choice of which requires justification, are:

- drift resistance coefficients of the tires of the tractor wheels;
- ballast mass on the frontal axle of the tractor, expressed through its total mass M_b.

The dependences (12) were calculated by the following values of the parameters chosen for a two-machine sowing aggregate based on the MTZ-80 tractor [10]: $f_k = 0.16$; $M_a = 1980$ kg, $M_b = 1320$ kg, $M_s = 1580$ kg. However, theoretical formulas are applicable to all wheeled tractors and can be used to derive dependencies for a particular tractor. The speed of the movement of the sowing aggregate on the turning strip was varied within the range 1-3 m·s^{-1}. The turning angle of the driven wheels of the tractor, that is, the magnitude of the control action, was varied within the range 0.02-0.50 rad. For a stable turn of the sowing aggregate, one can assume that:

$$\dot{Y}_a=\dot{K}=0,\qquad(13)$$

The solution of the system of equations (12) on a PC in the Mathcad environment made it possible to obtain the following results. As analysis of the studies shows, when the resistance coefficient k_b varies within the range of 60-80 kN·rad^{-1}, the value of R_a increases but Y_a decreases. However, practically these changes are insignificant (as for k_a = 180-210 kN·rad.$^{-1}$), which is determined by the small variation of the drift angles of the tires, both of the frontal and the rear wheels of the aggregating tractor. The results of investigations in the impact of the speed of the movement of the aggregate upon the parameters of its manoeuvre show that with the speed of the movement increasing from 1.0 to 3.0 m·s^{-1}, the turning radius varies little (Fig. 4).

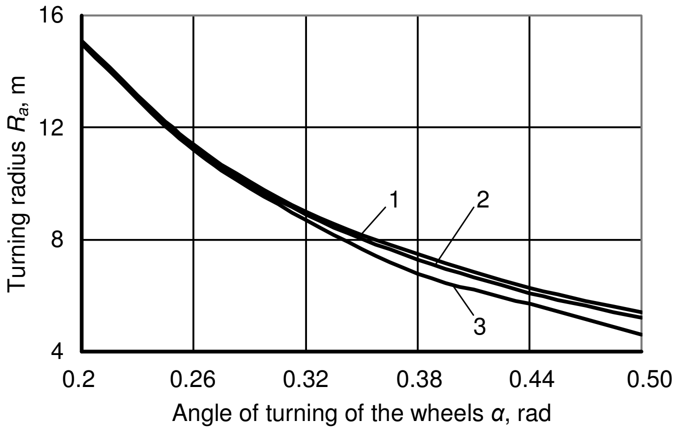

Fig. 4. **Dependence of turning radius R_a of sowing aggregate on turning angle α of driven wheels of tractor at various speeds of movement on turning strip V_t:**
1 – 1.0 m·s^{-1}; 2 – 2.0 m·s^{-1};3 – 3 m·s^{-1}

In general, this process (see Fig. 4) tends to decrease, which is more pronounced at a speed of the aggregate exceeding 2.0 m·s^{-1}.The result obtained needs an explanation, since more often the increase in the speed of the machine-and-tractor aggregate leads to an increase in its turning radius.

In our case, such a character of dependence (see Fig. 4) is caused by a decrease in the absolute value of the negative coordinate of the displacement of the turning centre of the sowing aggregate Y_a at gradual growth of V_t. When the speed of the movement of the aggregate on the turning strip is 3.0 m·s^{-1}, and the control action is greater than 0.32 rad, this coordinate assumes a positive value (Curve 3, Fig. 5).

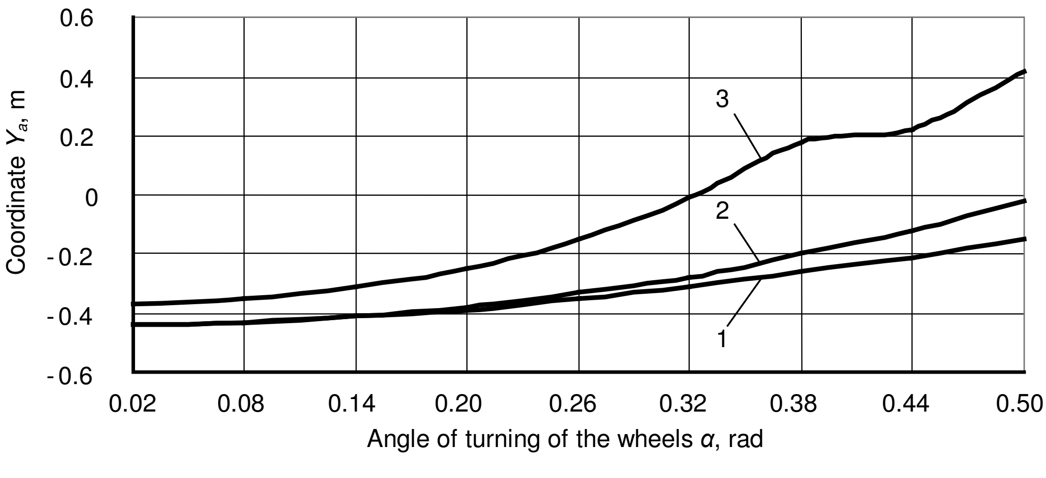

Fig. 5. **Dependence of coordinate Y_a on turning angle α of driven wheels of tractor at various speeds of their movement on turning strip V_t:**1 – 1.0 m·s^{-1}; 2 – 2.0 m·s^{-1}; 3 – 3 m·s^{-1}

And although the value of Y_a increases with a further increase in the control impact from 0.32 to 0.50 rad, the turning radius of the machine-and-tractor aggregate, instead of the logical (at first glance) increase, in fact gradually decreases (Curve 3, Fig. 4).

The explanation of this fact is based on the variation dynamics of the drift angles of the frontal (δ_b) and the rear (δ_a) tires of the tractor. The point is, when the sowing aggregate is moving on the turning strip at a speed of 3.0 m·s^{-1} with the control impact exceeding 0.32 rad, the drift angle of the rear wheels of the tractor changes its direction to the opposite. At $\alpha = 0.5$ rad its value generally increases to 0.09 rad, which is almost equal to the drift angle of the tires of the frontal wheels of the aggregating tractor. At the same time the intensity, with which angles δ_b and δ_a are growing within the range of variations in the control impact $\alpha = 0.32$-0.50 rad, is different: in particular, for the first one it is higher than for the second one. Thus, if the value of the angle δ_a increases practically twice, when α increases from 0.32 to 0.50 rad, then the angle δ_b increases more than 90 times.

The resulting advance in the growth of the drift angle of the rear wheels of the aggregating tractor in relation to the drift angle of the tires of its frontal wheels determines a situation, in which the growth of the displacement coordinate of the turning centre of the two-machine sowing aggregate does not lead to an increase, but to a reduction in the radius of its manoeuvre on the turning strip. Increasing the draught resistance from the side of the seeders leads to an increase in the value of R_a. Thus, at $\alpha = 0.5$ rad and $V_t = 2.0$ m·s^{-1}, the increase in force P_f doubles the growth of R_a from 5.3 to 5.8 m (i.e. by 9.4 %). Under the impact of the draught resistance of the technological part of the aggregate (two seeders), the frontal axle of the tractor can be unloaded to a certain extent. As a result, this leads to a reduction in the drift coefficient of the tires of the driven wheels of the tractor and, consequently – to a corresponding change in the turning parameters of the aggregate. The vertical load on the driven wheels of the tractor can be changed by ballasting its frontal axle. Besides, in calculations one should take into account the corresponding increase or decrease in the rolling resistance of the frontal wheels of the tractor $-P_{fb}$ (see Fig. 2). As the mathematical simulation showed, ballasting the frontal axle of the tractor with a mass of 180 kg determines a reduction in the turning radius of the aggregate. Another thing is that it is noticeable only when the turning angle of the driven wheels of the tractor is greater than 0.32 rad (18°). At the maximum value of the control impact ($\alpha = 0.5$ rad), the reduction in the turning radius of the sowing aggregate because of the ballast on the front axle of the tractor is 0.8 m (i.e. 15 %). In this case, the displacement coordinate of the turning centre decreases as well. Besides, for the turning angle of the driven wheels of the tractor of more than 0.44 rad its value changes its sign from negative to positive (Fig. 6).

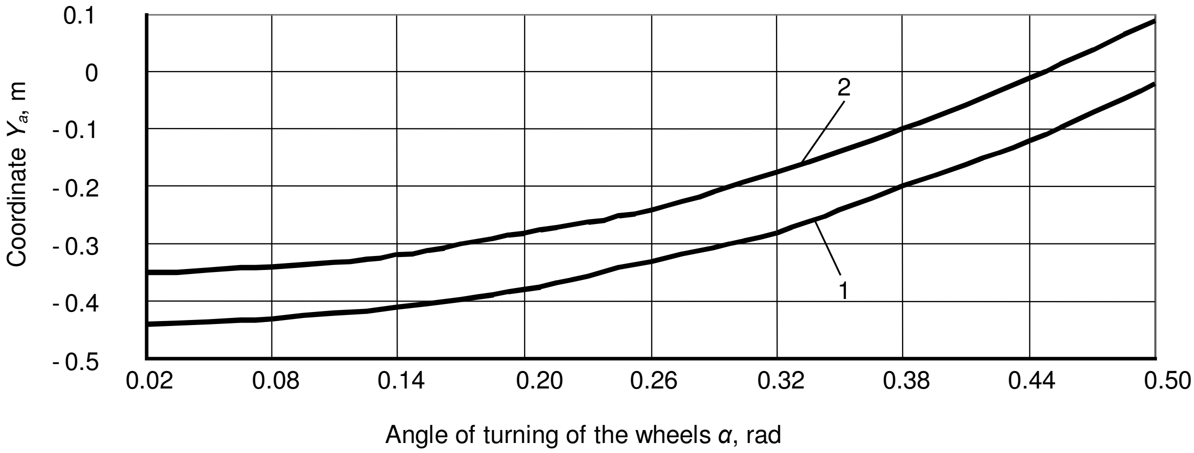

Fig. 6. **Dependence of coordinate Y_a on turning angle α of driven wheels of tractor with ballast on its frontal axle:** 1 – 0 kg; 2 – 180 kg

Conclusions

1. The turning process of a two-machine sowing aggregate does not lay any special restrictions on choosing the drift resistance values of the tires of the tractor wheels. If these values are varied within the limits of 60-80 kN·rad^{-1} – for the frontal wheels of the tractor and 180-210 kN·rad^{-1} – for its rear wheels, the turning radius of the aggregate increases, but the longitudinal displacement coordinate of the turning centre decreases. However, for practice these variations are not significant, which is due to a small (up to 4°) change in the drift angles of the tires of both axles of the aggregating tractor.

2. In order to improve the turning ability of a two-machine sowing aggregate, it is desirable to apply ballasting of the wheels of the frontal axle of the aggregating tractor. Thus, additional loads with a mass of 180 kg installed on it can reduce the turning radius of the aggregate. The most noticeable result of ballasting is at the turning angle of the driven wheels of the tractor – more than 0.32 rad (18º). At the maximum value of the control impact (α = 0.5 rad), the reduction in the turning radius of the aggregate due to the ballast of the frontal axle of the tractor is 0.8 m (i.e. 15 %).
3. As the speed of the aggregate increases from 1.0 to 3.0 $m \cdot s^{-1}$, the turning radius of the aggregate tends to decrease, which is more pronounced at a speed exceeding 2.0 $m \cdot s^{-1}$. Such a result is determined by an advanced increase in the drift angle of the rear driving wheels of the tractor in relation to the drift angle of the tires of its frontal driven wheels.

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