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THE STUDY OF MOVEMENT OF THE WIDE SPAN TRACTOR-BASED FIELD MACHINE UNIT WITH POWER METHOD OF ITS CONTROL

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Recently, rapid development of controlled traffic farming convincingly demonstrates the broad prospects of using the wide span tractor-based field machines throughout the world. The issue at hand lies in the fact that having a wide span tractor-based machine with steering-wheel system moving along the tracks of a constant technological track is not a rational option. According to the concept of bridge and rutting agriculture, it is advisable to subordinate the automated means of mechanization to the principles of the functioning of the coordinate transport system in which machines can move only in two mutually perpendicular directions and for implementation of which the field must have strictly defined dimensions. Therefore, a method of power steering similar to a crawler tractor (track-type tractor) can be more efficient in the automatic driving of bridge means of mechanization within the coordinate-transport system than a kinematic control. Furthermore, methodology utilized for selection of design schemes, parameters and operating modes of machine-tractor aggregates can not be used for study of dynamics of the wide span tractor-based field machine. Theoretical study is based on theoretical mechanics, theory of mobile energy facilities, statistical dynamics and theory of automatic control of linear dynamical systems with reproduction of statistically random control and disturbing input effects. Purpose of the research lies in development of a dynamic model of plane parallel motion in the horizontal plane of a wide span tractor-based field machine unit using a power (onboard) method of control, which would allow investigation of impacts of the control parameters and disturbing influences on the controllability and stability of its motion. Mathematical models have been developed and new regularities of the straightforward parallel movement of the wide span tractor-based field machine unit for controlled traffic farming have been obtained. The results obtained allow the validation of new schemes, design parameters and modes of operation with acceptable controllability and stability of movement in the horizontal plane with a power control method of the chassis.

Keywords: controlled traffic farming; wide span tractor-based machine; theoretical research; power method of machine motion control

Development and dissemination of "precision farming" systems in recent years, as well as development of information technologies, have made it possible to formulate the concept of managed adaptive farming, i.e. to determine the place and role of mechanized technologies or machines in the production of cost-effective products (Adamchuk, 2001). In association to this, the exploitation of mechanization in agricultural production should be as effective as possible.

Recent rapid development of controlled traffic farming – CTF (Chamen, 2015; Kingwell and Fuchsbichler, 2011) convincingly demonstrates the broad prospects of using the wide span tractor-based field machines throughout the world (Chamen, 1992; Chamen, 1994; Onal, 2012; Pedersen, 2011; Chamen, 2000; Pedersen et al., 2013).

Like any other mobile power unit, wide span tractor-based field machine for CTF can be considered a complex control object that can be adapted to manual or automatic control and is built on the turn-around kinematic and force principles (Chamen, 1992; Chamen, 1994; Onal, 2012; Pedersen, 2011; Chamen, 2000; Pedersen, 2013).

The issue at hand lies in the fact that having a wide span tractor-based machine with steering-wheel system moving along the tracks of a constant technological track is not a rational option. According to the concept of bridge and rutting agriculture, it is advisable to subordinate the automated means of mechanization to the principles of the functioning of the coordinate transport system in which machines can move only in two mutually perpendicular directions and for implementation of which the field must have strictly defined dimensions. Therefore, a method of power steering similar to a crawler tractor (track-type tractor) can be more efficient in the automatic driving of bridge means of mechanization within the coordinate-transport system than a kinematic control.

All known studies on the given topic are aimed at studying the dynamics of the movement of agricultural units built on the basis of traditional tractors and do not

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deal with the solution to this problem. Moreover, power method of steering is usually selected in relation to a crawler tractor (track-type tractor).

Accumulated scientific and practical experience of using traditional machine-tractor units in CTF allowed substantiation of certain requirements to the parameters of the constant technological track and power units (Bulgakov et al., 2017). However, these requirements do not take into account the atypical layout of the wide span tractor-based field machines, specificity of their aggregation and operating conditions, and it is necessary to specify them more precisely.

Purpose of the research lies in development of a dynamic model of plane parallel motion in the horizontal plane of a wide span tractor-based field machine unit using a power (onboard) method of control, which would allow investigation of impacts of the control parameters and disturbing influences on the controllability and stability of its motion.

Material and methods

In case of mathematical modelling of the motion in horizontal plane of the wide span tractor-based machine unit, model of its functioning as a dynamical system can be perceived as a form of reactions to input control and disturbing influences uniquely determining its controllability and stability of its motion.

Theoretical study is based on theoretical mechanics, theory of mobile energy facilities, statistical dynamics and theory of automatic control of linear dynamical systems with reproduction of statistically random control and disturbing input effects.

Particularly, amplitude and phase frequency characteristics are based on an estimation analysis of influence of the circuit and investigated wide span tractor-based field machine parameters on its motion controllability and stability.

Since considered dynamical system is a follower, the amplitude-frequency characteristic must be equal to one in the operating frequency range and the phase-frequency characteristic must be equal to zero in the control process. Differential equations of the plane-parallel motion of a wide span tractor-based machine in the horizontal plane will be in the form of Lagrange equations of the second kind:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right)-\frac{\partial T}{\partial q_i}=Q_i \qquad (1)$$

where:
- T – kinetic energy of a mechanical system
- q_i – generalized coordinate
- i – number of a generalized coordinate
- Q_i – generalized force corresponding with the generalized coordinate q_i

Results and discussion

Wide span tractor-based field machine can be considered a relatively complicated dynamic system. Therefore, at this stage of studying the dynamics of the wide span tractor (vehicles), it is advisable to observe its simplified scheme in the form of a stationary linear model (Fig. 1). In multiple cases, such idealization of the system is quite effective for complex tractor-machine agricultural aggregates and their control systems, the dynamics of which have not been studied sufficiently as of now.

Presented scheme of forces (see Fig. 1) acting on the wide span tractor-based field machine with the power (onboard) control method shows that torque from the power unit (or power units) is transmitted separately to the left and right wheels. Influence of all forces acting on the agricultural implements of wide span tractor-based field machine can be expressed through their main vector R (the components R_x and R_y respectively) and the main moment M_R.

The nature of perturbations entirely depends on the design scheme of wide span tractor-based field machine and its technological purpose. Taking into account the foregoing assumptions, we assume that investigated wide span tractor-based field machine performs uniform moving at a speed V_0 with respect to the immovable horizontal plane XOY (Fig. 1). In the process of performing the work, its skeleton deviates from the initial position and receives additional velocities under the influence of random perturbations – its relative motion in relation to the plane $X_1O_1Y_1$ begins. In this case, the plane $X_tS_tY_t$, connected to the mass centre of mass of wide span tractor-based machine unit, wraps it in the plane $X_1O_1Y_1$ around the axis passing through the point S_t. This results in angle φ, which is formed by the longitudinal axis S_tY_t of wide span

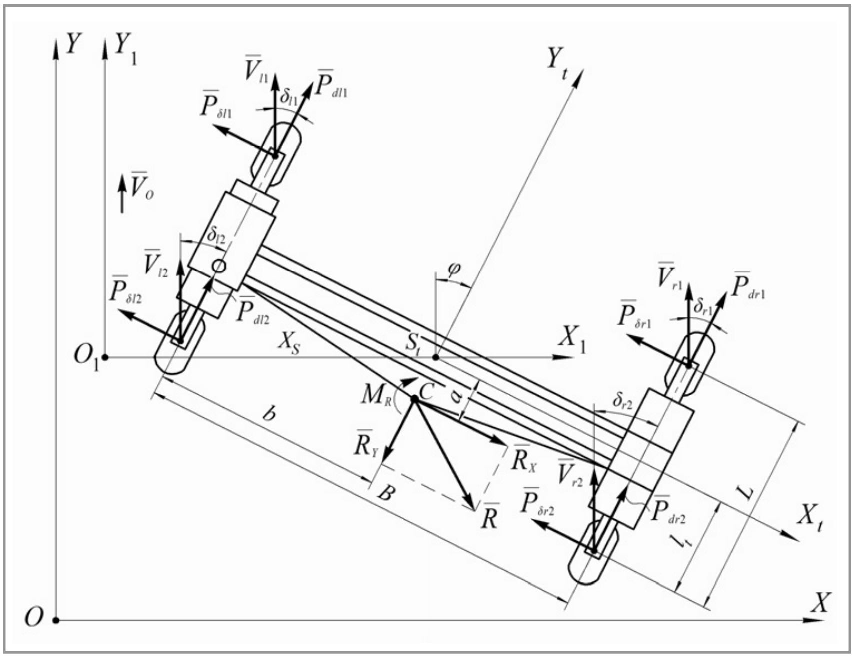

Fig. 1 Scheme of forces acting on the wide span tractor-based machine unit in the horizontal plane with the power (onboard) control method

tractor-based machine unit and axis O_1Y_1. In the process of relative motion, its mass centre moves along the axis O_1X_1, which is characterized by a change in the abscissa X_S.

Therefore, investigated wide span tractor-based machine unit has two degrees of freedom with respect to the plane $X_1O_1Y_1$, corresponding with two generalized coordinates: angle φ and displacement of the abscissa X_S of the centre of its masses S_t.

It is possible to include the following to the external forces acting on the wide span tractor-based machine unit with plane-parallel motion:

- driving forces P_{dl1}, P_{dl2}, P_{dr1}, P_{dr2} of the left and right sides, acting respectively in their centres;
- lateral forces $P_{\delta l1}$, $P_{\delta l2}$, $P_{\delta r1}$, $P_{\delta l2}$ resulting in displacement angles δ_{l1}, δ_{l2} and δ_{r1}, δ_{r2} of the wheels in the left and right part of the chassis unit;
- main vector R and main moment M_R of the forces acting from the side of agricultural implements.

Differential equations of the wide span tractor-based machine unit motion in relation to plane $X_1O_1Y_1$ (Fig. 1) were adapted to the form of Lagrange equations of the second kind.

In order to mathematically describe the lateral interaction of the wide span tractor-based machine unit with the field surface, a hypothesis of "lateral deviation" in linear interpretation is most frequently utilized. In this case, to determine the lateral horizontal forces in the places of contact between the wheels and soil, coefficients of resistance to the lateral bending of the tires are used according to the Rocard hypothesis:

$$\begin{aligned} P_{\delta l1} &= k_{l1}\times\delta_{l1} \qquad P_{\delta r1} = k_{r1}\times\delta_{r1} \\ P_{\delta l2} &= k_{l2}\times\delta_{l2} \qquad P_{\delta r2} = k_{r2}\times\delta_{r2} \end{aligned} \tag{2}$$

where:
k_{l1}, k_{l2} and k_{r1}, k_{r2} – resistance coefficients to deviation of the left and right wide span tractor-based machine unit wheels

System of equations was obtained during determining the angles of tire slip and lateral forces:

$$\left.\begin{aligned} \tan\delta_{l1} \approx \delta_{l1} &= \frac{\dot{X}_S + (L-l_t)\times\dot{\varphi} - V_0\times\varphi}{V_0} \\ \tan\delta_{l2} \approx \delta_{l2} &= \frac{\dot{X}_S - l_t\times\dot{\varphi} - V_0\times\varphi}{V_0} \\ \tan\delta_{r1} \approx \delta_{r1} &= \frac{\dot{X}_S + (L-l_t)\times\dot{\varphi} - V_0\times\varphi}{V_0} \\ \tan\delta_{r2} \approx \delta_{r2} &= \frac{\dot{X}_S - l_t\times\dot{\varphi} - V_0\times\varphi}{V_0} \end{aligned}\right\} \tag{3}$$

Kinetic energy of the wide span tractor-based machine unit relative to the $X_1O_1Y_1$ plane (Fig. 1) consists of two parts representing its translational and rotational motion:

$$T = \frac{M_t\times V_s^2 + J_t\times\omega_t^2}{2} \tag{4}$$

where:
M_t – weight of wide span tractor-based machine unit
V_s – linear velocity of the mass centre of wide span tractor-based machine unit relative to the plane
J_t – moment of inertia of wide span tractor-based machine unit in relation to its mass centre
ω_t – angular velocity of wide span tractor-based machine unit

It is obvious that:

$$\begin{aligned} V_s &= \dot{X}_S \\ \omega_t &= \dot{\varphi} \end{aligned} \tag{5}$$

By substituting the derivatives of angular and linear velocities (Eq. 5) to Eq. 4, we obtain:

$$T = \frac{1}{2}\left(M_t\times\dot{X}_S^{\,2} + J_t\times\dot{\varphi}^2\right) \tag{6}$$

Taking the derivatives with respect to the accepted generalized coordinates, after differentiation we obtain:

$$\left.\begin{aligned} M_t\times\ddot{X}_S &= Q_x \\ J_t\times\ddot{\varphi} &= Q_\varphi \end{aligned}\right\} \tag{7}$$

where:
Q_x and Q_φ – generalized forces determining the wide span tractor-based machine unit movement along the corresponding generalized coordinates

Taking into account the low values of attributes obtained in Eq. 7, the equation for determining the generalized forces will be as follows:

$$\begin{aligned} Q_x &= R_x - P_{\delta l1} - P_{\delta l2} - P_{\delta r1} - P_{\delta r2} \\ Q_\varphi &= M_R - R_x\times a + P_{dl1}\times b + P_{dl2}\times b - P_{dr1}(B-b) - \\ &-P_{dr2}(B-b) - P_{\delta l1}(L-l_t) + P_{\delta l2}\times l_t - P_{\delta r1}(L-l_t) - P_{\delta r2}\times l_t \end{aligned} \tag{8}$$

where:
B, b, a, L and l_t – design parameters, the nature of which is clear from Fig. 1

By substituting Eq. 8 to Eq. 7 and carrying out a series of transformations, we obtain a mathematical model of the wide span tractor-based machine unit movement in the horizontal plane with the power (onboard) control method in the differential form of recording:

$$\left.\begin{aligned} A_{11}\times\ddot{X}_S + A_{12}\times\dot{X}_S + A_{13}\times\dot{\varphi} + A_{14}\times\varphi &= R_x \\ A_{21}\times\ddot{\varphi} + A_{22}\times\dot{\varphi} + A_{23}\times\varphi + A_{24}\times\dot{X}_S &= M_R - R_x\times a + \\ +\left(P_{dl1}+P_{dl2}\right)b - \left(P_{dr1}+P_{dr2}\right)\times(B-b) & \end{aligned}\right\} \tag{9}$$

where:
$A_{11} = M_t$

$$A_{12} = \frac{k_{l1}+k_{l2}+k_{r1}+k_{r2}}{V_0}$$

$$A_{13} = \frac{\left[(L-l_t)\times\left(k_{l1}+k_{r1}\right) - l_t\times\left(k_{l2}+k_{r2}\right)\right]}{V_0}$$

$$A_{14} = -\left(k_{l1}+k_{l2}+k_{r1}+k_{r2}\right)$$
$$A_{21} = J_t$$
$$A_{22} = \frac{\left[\left(k_{l1}+k_{r1}\right)\times\left(L-l_t\right)^2 + \left(k_{l2}+k_{r2}\right)\times l^2{}_t\right]}{V_0}$$
$$A_{23} = \left[\left(k_{l2}+k_{r2}\right)\times l_t - \left(k_{l1}+k_{r1}\right)\times\left(L-l_t\right)\right]$$
$$A_{24} = \frac{\left[\left(k_{l1}+k_{r1}\right)\times\left(L-l_t\right) - \left(k_{l2}+k_{r2}\right)\times l_t\right]}{V_0} = A_{13}$$

In the operator form of the recording, Eq. 9 has following form:

$$\left.\begin{aligned} &K_{11}\times X_S(s)+K_{12}\times\varphi(s)=F_{11}\times P_{dl1}+F_{12}\times P_{dl2}+\\ &\quad +F_{13}\times P_{dr1}+F_{14}\times P_{dr2}+F_{15}\times R_x+F_{16}\times M_R\\ &K_{21}\times X_S(s)+K_{22}\times\varphi(s)=F_{21}\times P_{dl1}+F_{22}\times P_{dl2}+\\ &\quad +F_{23}\times P_{dr1}+F_{24}\times P_{dr2}+F_{25}\times R_x+F_{26}\times M_R \end{aligned}\right\} \quad (10)$$

where:

$K_{11} = A_{11}\times s^2 + A_{12}\times s$ $K_{12} = A_{13}\times s + A_{14}$
$K_{21} = A_{24}\times s$ $K_{22} = A_{21}\times s^2 + A_{22}\times s + A_{23}$
$F_{11} = 0$ $F_{12} = 0$
$F_{21} = b$ $F_{22} = b$
$F_{13} = 0$ $F_{23} = -(B - b)$
$F_{14} = 0$ $F_{15} = 1$
$F_{24} = -(B - b)$ $F_{25} = -a$
$F_{16} = 0$ $F_{26} = 1$
$s = \frac{d}{dt}$ – operator of differentiation

Constructed mathematical models (Eqs. 9 and 10) allow estimation of stability and controllability of motion of practically any wide span tractor-based machine unit with power (onboard) control method.

In mathematical model of the dynamical system under consideration in the operator form of record (Eq. 10), driving forces P_{dl1}, P_{dl2}, P_{dr1}, P_{dr2} are control action operators. Furthermore, characteristics of disturbing effect are as follows: component R_x of the principal vector R of the resistance of the agricultural implement and main moment of M_R.

Subsequently, attention will be paid to the variant of driving of wide span tractor-based machine unit by transferring power from its power unit (or units) separately to the wheels on the left and right sides. For this case, mathematical model of the dynamic system in the operator form of recording (Eq. 10) will take following form:

$$\left.\begin{aligned} &K_{11}\times X_S(s)+K_{12}\times\varphi(s)=N_{11}\times P_{dl1}+N_{12}\times R_x+N_{13}\times M_R+N_{14}\\ &K_{21}\times X_S(s)+K_{22}\times\varphi(s)=N_{21}\times P_{dl1}+N_{22}\times R_x+N_{23}\times M_R+N_{24} \end{aligned}\right\} \quad (11)$$

where:

$K_{11} = A_{11}\times s^2 + A_{12}\times s$
$K_{12} = A_{13}\times s + A_{14}$
$N_{11} = F_{11} = F_{12} = 0$
$N_{12} = F_{15} = 1$
$N_{13} = F_{16} = 0$
$K_{21} = A_{24}\times s$
$K_{22} = A_{21}\times s^2 + A_{22}\times s + A_{23}$
$N_{21} = F_{11} = F_{12} = b$
$N_{22} = F_{25} = -a$
$N_{23} = F_{26} = 1$
$N_{14} = F_{13}\times P_{dr1} + F_{14}\times P_{dr2} = 0$
$N_{24} = F_{23}\times P_{dr1} + F_{24}\times P_{dr2}$
$s = \frac{d}{dt}$ – operator of differentiation

In order to describe the amplitude and phase-frequency characteristics of the expressions for transfer functions of the plane-parallel motion dynamics in the horizontal plane of wide span tractor-based machine unit with power (onboard) control method, these characteristics will have the following:

1. according to the control action:
   – with linear movement X_S:

$$W_1 = \frac{D_1 + \left(\frac{1}{2}L - l_t\right)\times D_2}{D_\Delta} \quad (12)$$

   – in relation to the movement course angle φ:

$$W_2 = \frac{D_2}{D_\Delta} \quad (13)$$

2. according to the disturbing effect of force R_x:
   – with linear movement X_S:

$$W_3 = \frac{D_3 + \left(\frac{1}{2}L - l_t\right)\times D_4}{D_\Delta} \quad (14)$$

   – in relation to the movement course angle φ:

$$W_4 = \frac{D_4}{D_\Delta} \quad (15)$$

where:

D_Δ, D_1... D_4 – determinants, expressions of which are defined as follows:

$D_\Delta = K_{11}\times K_{12} - K_{12}\times K_{21}$
$D_1 = -N_{21}\times K_{12} = -b\times(A_{13}\times s + A_{14})$
$D_2 = N_{21}\times K_{11} = b\,(A_{11}\times s^2 + A_{12}\times s)$
$D_3 = K_{22} - K_{12}\times N_{22} = A_{21}\times s^2 + (A_{22} + a\times A_{13})\times s + A_{23} + a\times A_{14}$
$D_4 = K_{11}\times N_{22} - K_{21} = -a\times A_{11}\times s^2 - (a\times A_{12} + A_{24})\times s$

Physical object of the theoretical study was the prototype of wide span tractor-based machine unit for controlled traffic farming (Kuvachov et al., 2012; Bulgakov et al., 2017).

For assessing the controllability of wide span tractor-based machine unit, the amplitude and phase-frequency characteristics of the control action were determined (Figs. 2–4). Analysis of the characteristics has shown that its controllability depends essentially on the size of the track B

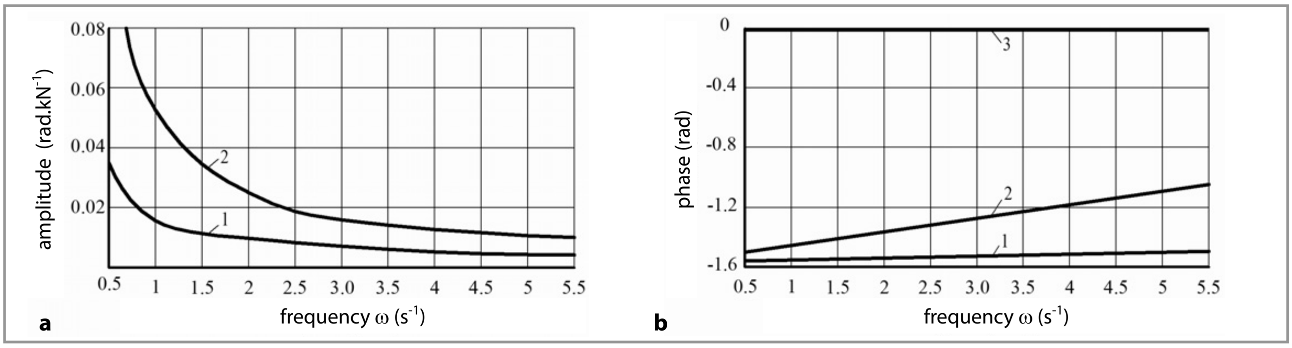

Fig. 2 Amplitude (a) and phase-frequency (b) characteristics of the oscillations of the course angle φ of wide span tractor-based machine unit with onboard control at different values of the track size
1 – B = 3 m; 2 – B = 9 m; 3 – ideal characteristi

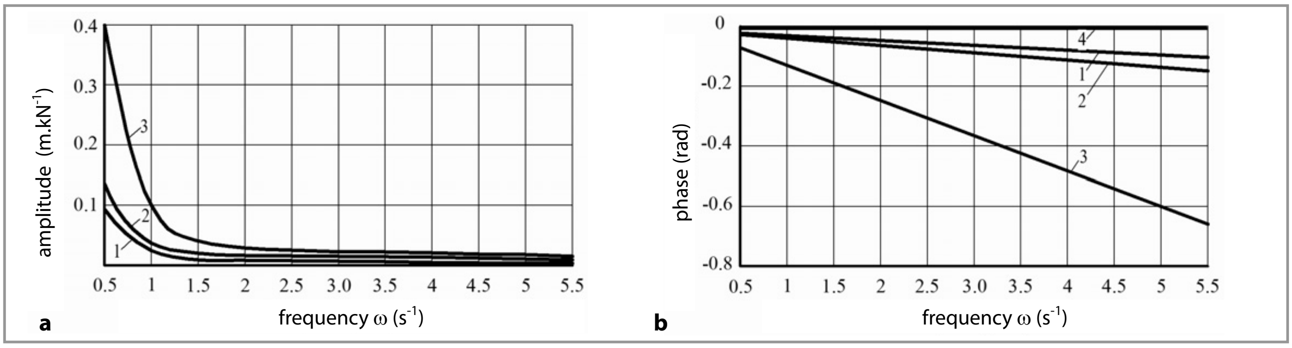

Fig. 3 Amplitude (a) and phase-frequency characteristics (b) of oscillations X_S of the lateral deviation of wide span tractor-based machine unit with force control method. Various values of the track size B were considered
1 – B = 2 m; 2 – B = 3 m; 3 – B = 9 m; 4 – ideal characteristic

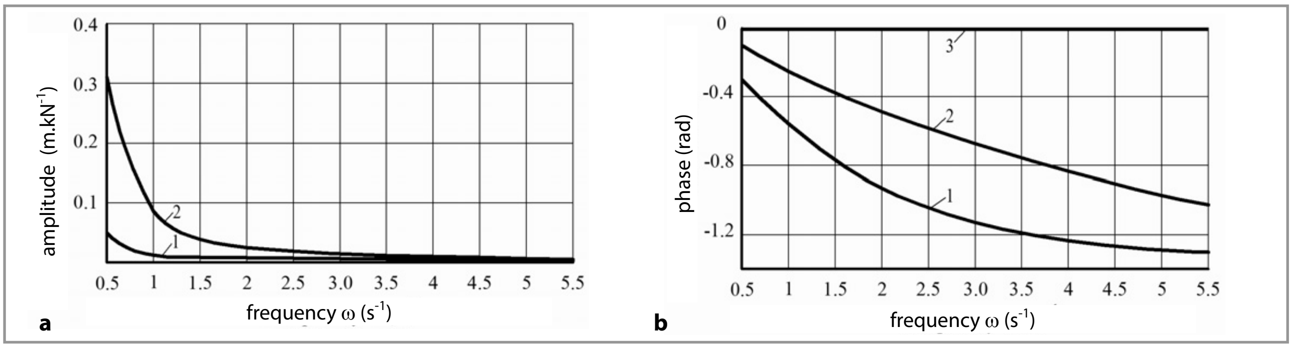

Fig. 4 Amplitude (a) and phase-frequency characteristics (b) of oscillations X_S of the lateral deviation of a wide span tractor-based machine unit when there is used as a control action the force control method during its work. The different values of the forward speed of the machine were considered
1 – 1 m·s^{-1}; 2 – 3 m·s^{-1}; 3 – ideal characteristic

(Figs. 2 and 3). The increase in the controlling action increases with an increment in the value of the wide span tractor-based machine unit track (Figs. 2a and 3a). This process is most pronounced at the driving force oscillation frequencies close to zero. At the same time, maximum amplitude of the transverse deflection for the investigated wide span tractor-based machine unit, the track size of which is B = 3 m, is at the level of 0.12 m per 1 kN of oscillations P_{dl} (Fig. 3a).

With an increase in its track to B = 9 m, the amplitude of transverse deflection increases to 0.4 m·kN^{-1}, what can practically lead to overshooting of the dynamic system and the complexity of managing the wide span tractor-based machine unit.

In relation to the above analysis, it can be stated that when the wide span tractor-based machine unit is operating at a high speed mode (close to 3 m·s^{-1}), it is possible to obtain satisfactory and acceptable controllability only with an effective controlling system.

Wide span tractor-based machine unit response to the input signal is significantly less delayed, what is desirable since phase-frequency characteristics of the course-angle fluctuation φ approach the ideal value with an increase in the size of its track (Fig. 2b).

Such nature of the effect of a track of the wide span tractor-based machine unit constructive size on the frequency characteristics of its controllability can be explained by the increase in its inertia (the moment of inertia), which enhances the response of dynamic system to input.

Speed of its movement has a significant effect on the controllability of wide span tractor-based machine unit (Fig. 4).

With an increase in the movement speed by 3 times (Fig. 4), there is multiplication by 10 times in the input control action at low frequencies close to 0.5 s^{-1}; at frequencies $\omega > 2.5\ s^{-1}$ at low speed, the system practically does not react to the controlling actions.

Conclusion

1. As a result of the conducted research, it was established that the steering-ability of the wide span tractor-based machine with the power steering control method is significantly worsening with the increase in the forward speed regime. Therefore, desired increase in the speed of the wide span tractor-based machine to 3 $m \cdot s^{-1}$ results in the increase in the control effect at the most characteristic low-frequency range (up to 2 s^{-1}) by almost 10 times. Consequently, the implementation of a high-speed mode (3 $m \cdot s^{-1}$ and higher) requires additional studies related to the use of more efficient automated steering systems that allow a satisfactory steering ability of the wide span tractor-based machine.
2. At low speeds of the wide span tractor-based machine (1–2 $m \cdot s^{-1}$), its steering is quite satisfactory. In this case, upgrading the traditional tractors with serial automation will allow for an efficient implementation of steering power control method of the wide span tractor-based machine in practice.
3. Theoretical study has shown that although with less intensity, the steering-ability of the wide span tractor-based machine with power control method is significantly influenced by the width of its track. For existing models of wide span tractor-based machines, with an increase in the track width from 3 to 9 m, the amplification of the reaction to the control effect in the low-frequency range (up to 2 s^{-1}) reaches a three-fold increase. Despite the decrease in the magnitude of the delay in this reaction of the wide span tractor-based machine to the steering effect, it should nevertheless be ascertained that the controllability is thus more complicated.

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