STUDY OF PASSIVE STEERING OF WIDE SPAN VEHICLES WITH POWER-DRIVEN STEERING METHOD

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Abstract. One of the defining areas for further research in the world is the development of a set of technological measures for the introduction of resource-saving technologies and technical means, ensuring reduction in the need for material, technical and energy resources. The introduction of track and bridge systems in farming, the basis of which is a wide-span bridge traction vehicle, is really promising in this respect. The development of power-driven agricultural axle traction machines brings forward the necessity of setting and solving the problems of uncontrolled (passive) driving with its own tasks and solution methods. The aim of this research is to investigate uncontrolled passive steering of a bridge vehicle with power steering. The methodological basis of the theoretical research was the system approach, mathematical modelling, the laws of theoretical mechanics, the theory of tractors and vehicles, information technology and the use of PCs. A prototype of a wide span vehicle has been used as the object of experimental investigations. As a result of this research, it was found that the maximum value of asymmetrically applied shear pulling force of the wide span vehicle corresponds to the direction when its line of action passes through the centre of mass. For 1 kN of traction resistance of the bridge machine under study, the lateral slip when it moves along the compacted soil track of a constant tramline for each 1 m of the distance travelled was 0.011…0.015 m. In any deviation from this direction, there is an instantaneous rotational movement (shear) of the wide span vehicle where the total shear force is less than the maximum value. The anisotropy of this process results in a reversal of the hodograph towards a lower coefficient of traction of the wide span vehicle thrusters on the bearing surface of the permanent technological track. The adequacy of the meta-mathematical models of the passive steering of the bridge vehicle with the power method of control allows the solution of problems such as calculation of the minimum turning radius, evaluation of the technological track width, calculation of the maximum traction forces, selection of the rational control scheme under steady driving conditions, calculation and reduction of power on the turn, calculation of the maximum dynamic loads at the moment of active driving and others.

Key words: controlled traffic farming, bridge vehicle, power steering, passive steering, research, model.

Introduction

A promising direction for further agricultural development worldwide is the introduction of innovative technologies, which include the track farming system [1-5]. The latter provides the basis for the automation and robotisation of most crop production processes, ensures the effective implementation of precision and digital farming and offers other significant benefits [1-10]. A wide span tractor is an agricultural power tool with a long support beam. Its distinguishing feature from other power driven vehicles is that it moves along permanent technological tracks, located at a distance equal to its span, in the area in which the agricultural tools are placed. An example of ASA-Lift WS 9600 WS wide span tractor is shown in Fig. 1 [11]. In the future, the wide span tractor will be in demand not only as a traction machine, but also as the power base for various wide span farming operations [10]. Given the general structure of the chassis and the steering mechanism of axle-driven machines, it has been scientifically proven that the simplest option is the on-board (power-driven) steering. These machines have motor wheels on two non-steerable axles and turn horizontally by varying the rotation speed of the front and rear wheels on the right and left side of the machine [12]**.** Despite the variety of specialised technical equipment, a curved movement (turning) takes place in the technological cycle of a wide span vehicle [13-14]. The peculiarity of operating wide span machines is that during operation they can make not only active (controlled) turns, but also passive ones, making a curvilinear movement not under the controlling influence of the operator, but under the influence of external forces [15]. An example of

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passive steering is a wide span vehicle steering away from a straight line under the influence of applied traction resistance load of an agricultural tool [16].

Fig. 1. **Wide span tractor ASA-Lift WS 9600 WS [11]**

The development of power-driven agricultural wide span vehicles has brought forward the need to set and solve the problem of unguided (passive) drifting with its own challenges and solution methods.

Research on the passive steering of traditional mobile machines is scarce and usually focuses on particular problems. For example, the classical theory of crawler turning was first developed as a theory of controlled curvilinear motion [17]. Scientific and practical design needs of wheeled tractors [18-19] defined a number of problems and the methods for their solution: calculating traction and power balances, skid conditions, stability, controllability and others. Scientific partial solutions to the problem of passive steering of traction machines, in contrast to controlled turning problems, are not always unambiguous.

Of all the passive steering problems of wide span vehicles, the most interesting ones are those of touching and steering. These issues have received little attention in the scientific literature.

Of course, the issues involved are not new and there are some mathematical models that describe such phenomena. For example, such is the model of the agricultural tractor under the influence of an eccentrically applied load on the hook [20-23]. Most of the known mathematical models are based on the theory of lateral drift and focus mainly on the kinematics of motion [24-26]. In engineering practice, however, one of the main questions in the study of the turning process of agricultural machines is the formation of force factors on the ground. The reason for this is that the kinematics of movement can always be corrected by the driver using the necessary steering actions and that loads resulting in various malfunctions must already be considered when designing the machine.

Attempts are known to apply to models of crawler and wheeled vehicles with non-swivelling bearings and inboard pivoting the shear force models of solid bodies on rough surfaces (based on pure friction between absolutely solid bodies) [13-14]. However, these models are dedicated to an active turnaround. The aim of the research is to investigate the uncontrolled passive steering of a wide span vehicle with power steering. The object of the study is the process of uncontrolled passive driving of a wide span vehicle. The subject of the research is the regularities of force and trajectory parameters of the wide span vehicle during its uncontrolled passive steering.

Materials and methods

The methodological basis for the theoretical research was the systems approach, mathematical modelling, the laws of theoretical mechanics, tractor and vehicle theory, information technology and the use of PCs. Experimental studies were carried out using both conventional and developed methods and included the use of modern and specially designed equipment. The research data was processed on a personal computer using the probability theory, regression and correlation spectral analysis.

A prototype of a four-wheel wide span vehicle was used for the experimental studies (Fig. 2). The wheelbase width of the prototype wide span vehicle (Fig. 2) is 3.5 m, the longitudinal base is 2.3 m, and the tyres are 9.5R32. The control method of the wide span vehicle is power onboard. Experimental studies were carried out in a specially equipped laboratory, where a permanent technological track was artificially created on the ground for the driving of a wide span vehicle on it.

Fig. 2. **Prototype four-wheel wide span vehicle**

Results and discussion

Let us investigate the process of passive steering of a wide span machine with a power onboard control method at the moment of the beginning of its curvilinear motion under the action of external forces without controlling influence from the driver. In this case, the wide span machine deviation from rectilinear motion, in the general case, is an unsteady turn with a variable radius. At low speeds and the absence of inertial forces, the motion of the wide-span machine can be represented as static at each moment of time, which allows us to use the model of quasi-static rotation.

When modelling the problem, related to the force of the momentum of moving (plane-parallel shear) a wide span vehicle with a power control, within the framework of the imposed resulting relations, the following assumptions are made: the physics of the wide span vehicle moving process is the same for both wheeled and tracked propulsion units; all elementary forces arising in the contact of the thrusters with the soil trace of a permanent track are combined friction and traction forces; any elementary force in the contact of the thruster with the trace of a permanent track must not exceed the traction limit and is directed in the opposite direction from the speed of expected shift of this point; the contact of the thruster with the soil is considered as flat pads.

Taking into account the non-uniformity of the traction resistance of the working bodies of agricultural implements over the entire width of the bridge machine, we consider the case of a hook load asymmetrically applied to it with a centre at point K (Fig. 3). The external hook load P, acting from agricultural implements, which is determined by their shape, depth of penetration into the soil, etc., forms an angle β with the longitudinal axis of the bridge machine and mainly determines its withdrawal.

The centre of mass of the bridge machine (point S) in this case begins to make a curvilinear movement around the point O, which is taken as the origin of the considered fixed horizontal area xOy. In this case, the distance from the centre of mass of the bridge machine to the point O at the initial moment of time is equal to x_0. Further, we assume that at equal theoretical speeds of movement of the wheels of the left and right sides of the bridge machine, their centres of sliding coincide. According to the theory of friction of a tractor with an onboard (power) method of its control [27], the resulting reaction from the bearing surface of the soil to the bridge machine will be brought to the centre of sliding (point C, Fig. 3).

Let the wide span vehicle deviate from the rectilinear path under the action of an external force (Fig. 3). At the same time, elementary forces arise in the contact of the vehicle's propulsor with the soil trace of a permanent track and reach a certain limiting value in terms of traction. The direction of each elementary force in plane-parallel (instantaneous rotational) motion of the bridge machine is perpendicular to its distance to the instantaneous sliding centre (point with zero sliding speed). The addition of elementary forces, which are different in direction, is carried out by bringing them to a certain centre (point C), which we take as the instantaneous centre of velocities.

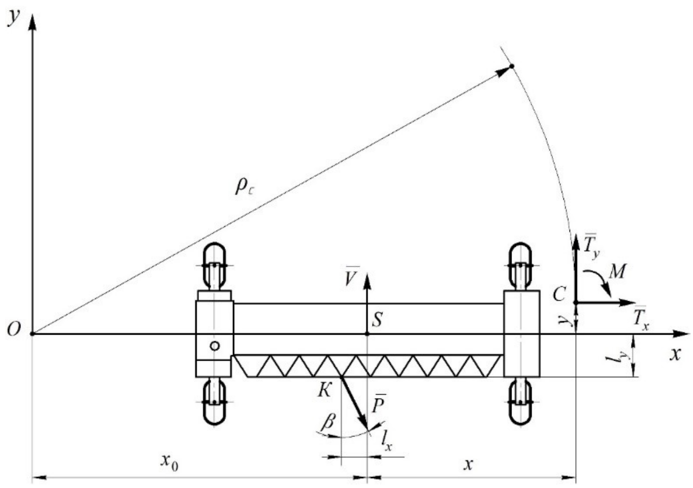

Fig. 3. **Schematic diagram of a wide span vehicle with the power method of its control**

With equal theoretical speeds of movement of the propellers of the left and right sides of the bridge machine, the centres of sliding of their supporting platforms coincide (point *C*, Fig. 3) and are removed from the centre of mass of the bridge machine at a distance *x*. Then the radius of curvature of the trajectory of point *C* (Fig. 3) is equal to:

$$\rho_c = x_0 + x\,, \tag{1}$$

where x_0 – initial coordinate of the centre of mass of the wide span vehicle in the coordinate system *xOy*, m;
x – current coordinate of the instantaneous velocity centre of the wide span vehicle in the coordinate system *xOy*, m.

Thus, the problem of constructing the trajectory of the instantaneous velocity centre of the bridge machine is reduced to finding the values x_0 and *x* in the coordinate system *xOy*.

Values x_0 and *x* are easily calculated when solving the problem of moving a wide span vehicle and written in the form of equilibrium conditions of the vehicle at the initial moment of time.

Since the curvilinear motion of the bridge machine as a result of its withdrawal occurs at low speeds, the equilibrium condition for an arbitrary plane system of forces has the form (2):

$$\begin{cases} l_y \cdot P \cdot \sin\beta + l_x \cdot P \cdot \cos\beta + x \cdot T_y - y \cdot T_x - M = 0 \\ P \cdot \sin\beta + T_x = 0 \\ -P \cdot \cos\beta + T_y = 0 \end{cases} \tag{2}$$

where T_x, T_y – are the projections of the resulting reaction from the soil on the bridge machine;
M – is the resulting moment of friction in the contact of the support wheels of the left and right sides of the bridge machine with the soil (the moment of resistance to rotation);
P – external asymmetrically applied drag force of agricultural machines and implements, kN;
β – angle of traction resistance force application of agricultural machines and implements, deg;
l_x, l_y – shoulders of the external force components relative to the instantaneous velocity centre, m.

The force factors included in the equations T_x, T_y, *M*, arising in the contact of the thrusters of the wide span vehicle with the ground, are functions of the coordinate *x* and take into account the deformative properties of the soil. To identify the direction of the maximum shear force of the wide span vehicle, caused by traction resistance of agricultural machines and implements, let us build a hodograph based on the mathematical model (2), where we identify the values of the limiting force P_{max} asymmetrically applied to the load on the wide span vehicle. A complete study of all possible directions

(β = 0...360º) made it possible to obtain the dependence of the limiting value of the force P from its angle of inclination (Fig. 4).

The analysis of the dependence in Fig. 4 showed that depending on the direction β of the external force P its limiting value changes. The maximum value of the shear force P_{max} corresponds to the direction when its line of action passes through the centre of mass of the wide span vehicle. This particular case characterizes progressive sliding, where the shear force is equal to the adhesion limit. In any deviation from this direction, there is instantaneous rotational motion (shear), and the total shear force is less than the maximum value of $P < P_{max}$. The hodograph inclination angle 69 deg characterizes the direction of the translational shear when the shear force passes through the centre of mass and is equal to the cohesion limit P_{max} = 10 kN. In all other cases, instantaneous rotational shear takes place. The maximum value of the transverse shear force P_{xmax} is observed at a certain direction β = 43 deg and is P_{xmax} = 2 kN, which is slightly less than the projection of the cohesive limiting force 10·cos 69° = 3.5 kN. Anisotropy of the interaction leads to a decrease in the maximum shear force P_{max} and the reversal of the hodograph towards a lower adhesion coefficient. To verify experimentally the mathematical model (2), the investigated wide span vehicle moved in a straight line with a constant speed (V = 0.3...0.5 m·s^{-1}) during the experiment. The tractive force P was measured every 10 m of travel: its direction β and the value of lateral deviation Δx from the rectilinear trajectory (Fig. 5). The error in estimating the traction resistance was ±0.05 kN, and the angle β was ±1 deg.

The adequacy of the model (2) of passive driving of the wide span vehicle was evaluated by comparing the experimental and calculated trajectories of its movement (Fig. 5). In the first experiment the value of traction load of the wide span vehicle was 1.8 kN, and the average angle of the traction resistance force application of the agricultural implements was equal to 21 deg. In the second experiment, the traction load of the bridge machine was 0.8 kN, and the average angle of application of the drag force of the agricultural implements was 12 deg. The results of the experiments showed that in two experiments with different traction load acting on the bridge machine, the deviation of the experimental trajectories from the calculated ones on the path of 50 m did not exceed 11.2%.

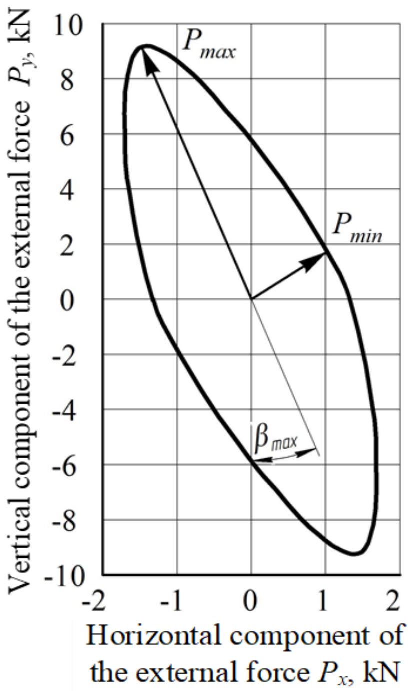

Fig. 4. **Hodograph of the force *P* of traction resistance shifting of the wide span vehicle at passive turning**

It has been established by the research that in the case when the shear force of traction resistance passes through the centre of mass of the bridge machine, for every 1 kN of its traction resistance, the value of the lateral slip when moving along a compacted soil track of a constant tramline for every 1 m of the distance travelled, the value of the lateral slip is 0.011...0.015 m. Thus, it can be assumed that when the bridge machine moves over a run length of 500 m with a traction resistance of 10 kN, its lateral slip can reach 55 m. Therefore, the rational aggregation of bridge machines and the automation of their driving in the wake of a constant technological track will make it possible to have a sufficiently high and stable straightness of their course.

Also, the results of the experiments showed that there is no bridge machine shear when the shear force is less than some limiting value.

Thus, the considered models of the processes of passive driving of wide span vehicles with the power method of their control can have a fairly wide application in the calculations in their design, which will solve problems such as calculation of the minimum turning radius, evaluation of the width of the technological track, calculation of maximum traction forces, the choice of rational control scheme from the conditions of stable movement, calculation and reducing power on the turn, calculation of maximum dynamic loads at the moment of active driving and others.

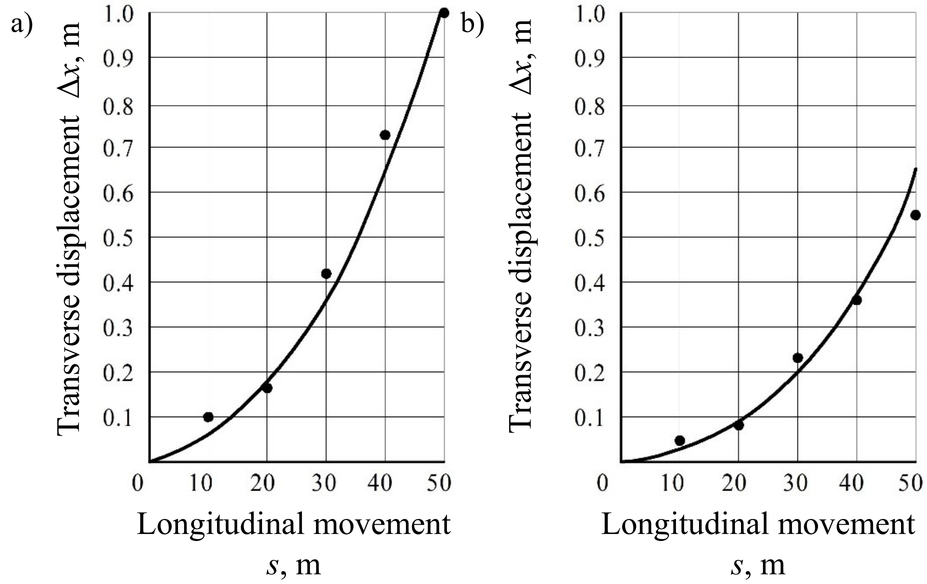

Fig. 5. **Trajectories of passive steering of a wide span vehicle with a power method of its control:** a – experiment No1 P_1 = 1.8 kN, β_1 = 21 deg; b – experiment No2 P_2 = 0.8 kN, β_2 = 12 deg

Conclusions

1. The problem of driving a slow-moving power-driven wide span vehicle moving along the soil traces of a perm technological track under the influence of an external eccentrically applied tractive force resistance of agricultural machines and implements is solved unambiguously only as a driving away problem. If the external force of traction resistance does not exceed the limit value for a given line of its action, the vehicle moves straight ahead without deviation, otherwise the problem has no unambiguous solution.
2. The maximum value of asymmetrically applied shear force of traction resistance of the wide span vehicle corresponds to the direction when its line of action passes through the centre of mass. For 1 kN of traction resistance of the bridge machine under study, the lateral slip when it moves along the compacted soil track of a constant tramline for each 1 m of the distance travelled was 0.011…0.015 m. At any deviation from this direction, there is an instantaneous rotational motion (shear) of the machine, where the total shear force is less than the maximum value. The anisotropy of this process leads to a reversal of the hodograph in the direction of a lower coefficient of traction of the wide span vehicle thrusters with the bearing surface of the constant tramline. Therefore, the rational aggregation of bridge machines and the automation of their driving in the wake of a constant technological track will make it possible to have a sufficiently high and stable straightness of their course.
3. The adequacy of meta-mathematical models of the passive steering of the wide span vehicle with the power method of its control allows to solve such problems as calculation of the minimum radius of turn, evaluation of the width of the technological track, calculation of the maximum traction

forces, selection of a rational control scheme from the conditions of stable movement, calculation and reduction of power on the turn, calculation of the maximum dynamic loads at the moment of active driving and others.

Author contributions

Conceptualization, V.A.; methodology, S.I. and V.B.; software, V.A. and V.K.; validation, V.K. and V.B; formal analysis, V.B and J.O.; investigation, V.B., S.I., A.R. and I.B..; data curation, V.A., V.K, A.R. an I.B.; writing–original draft preparation, V.B.; writing–review and editing, V.K. and V.B.; visualization, V.K., I.B.; project administration, V.A.; funding acquisition, S.I. All authors have read and agreed to the published version of the manuscript.

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