Measure of the deflections from linear trajectory of a skid-steer gantry tractor during its motion

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***Abstract*— The aim of the research is to study the plane-parallel movement in a horizontal plane of a wide-span gantry tractor equipped with a skid-steering system. The theoretical studies are based on the foundations of the tractor theory and theoretical mechanics. As a results, it was found that the implementation of the skid-steering system on the gantry tractor leads to a significant change in its yawing angle by an average of 1 degree per 0.1 s and its insignificant lateral displacement. Rotations as well as transversal displacements of the longitudinal axis of the gantry vehicle from a pre-set trajectory require successive and consecutive rotations in the opposite directions to realign the machine to the tracks of the permanent traffic lanes. Experimental tests were performed using the skid-steer gantry tractor developed by the authors to evaluate the oscillations of the yawing angle and transverse displacements throughout the motion of the machine along the tracks of the permanent traffic lanes. The fluctuations were in the frequency range from 0 to 2 s^{-1} for both parameters.**

Keywords*— agricultural wide-span vehicle, controlled traffic farming, permanent traffic lanes, trajectory deviations measurement, mathematical modeling.

I. Introduction

Controlled Traffic Systems (CTF) use stable un-trafficked plots as production units, with wheel tracks on either side [1-3]. Conversely, these wheel tracks constitute permanent traffic lanes (PTL), exclusively devoted to all field machinery travels [4-6]. Usually gantry tractors, i.e., large-span vehicles, are used inside the CTF [7-9].

The gantry tractors have several features that significantly distinguish them from other types of energy used in agriculture, industry, and transport. It is, first, a large transverse base (track) – *K*, formed by a frame, on the ends of which there are left and right sides. Since the sides are located at a considerable distance from each other, it is necessary to provide individual drive for their running wheels, which are installed in pairs at each side in the form of moving one trail of the front and the rear driving wheels [10-13].

The stability safety condition of these wide-track agricultural tractors during their motion should be ensured by appropriate dimensions of longitudinal base – *L*. This parameter is especially important, because the working elements of agricultural implements are placed on the frame between two sides or strictly on the transverse axis of symmetry of the tractor, or at some distance from this axis [14-17]. As is known from the classical theory of the tractor, the ratio of its longitudinal base to the transverse base, (*L/K*), is an important geometric parameter that characterizes stable turns, throughout the execution of every technological process within agricultural production. This is since in the performance of field agricultural works, the PTL themselves are not perfectly straight, and in addition, there are significant size and direction of external disturbances by the soil and cultivated plants, which seek to constantly change the trajectory of the gantry agricultural unit [18-21].

In other words, throughout the motion of the gantry tractor inside the CTF, various factors (soil characteristic, forward speeds, uneven soil resistances, and so on), also interconnected with each other and continuously changing, strongly influence the established trajectory, giving rise to unbroken small yawing deviations and/or transverse movements of the vehicle. Moreover, considering that in this type of tractors the wide track is much greater than the wheelbase, the aforesaid deflections can cause significant irregular displacements of the working implements fixed at the frame between two sides of the machine. Therefore, by using gantry tractors for cultural operations to row-crops, the yawing deviations and/or the transverse movements from the set trajectories make that the working tools can damage or cut the plants, so reducing the machine working efficiency. Considering these aspects, it needs to keep at minimum these deflections for achieving high operative efficiencies.

Bearing in mind the aforesaid, the authors conceived and built an agricultural gantry tractor fitted with skid steering system, prepared to go in the tracks of permanent

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traffic lanes and to change direction by varying the speeds of the wheels [22].

The aim of the research has been to theoretically measure the deviations from the established trajectory of this type of skid steer gantry tractor, numerically simulating the conditions of its functioning. Furthermore, results of experimental evaluations about the oscillations of the aforesaid vehicle during its motion along PTL are reported.

II. Materials and Methods

A. The conceived and manufactured gantry

The authors have conceived and manufactured an electric traction gantry tractor suitable for transit along the permanent traffic lanes sited inside the controlled traffic farmings (Fig.1). Two Energolukss SIA AIR80B6 (Energolukss, SIA, Riga, Latvia) 3-phase electric asynchronous motors with nominal power of 1.1 kW were mounted on the right and left sides of the machine, respectively.

Each engine had an electronic control system and, by means of mechanical transmission, drove the motion of the wheels of the same side. The developed gantry tractor had track width and pitch of 3.5 m and 2.5 m, respectively. Furthermore, the operating weight was 1158 kg and the nominal pulling force 6.3 kN. The vehicle steering was obtained by appropriately modifying the revolutions of wheels placed on its sides [23].

B. Theoretical considerations

First, it should be noted that in qualitative performance of any technological process the gantry agricultural unit makes plane-parallel motion in a horizontal plane parallel to the field surface strictly on the tracks of PTL. However, throughout the process of its functioning, there are characteristic deviations of the large-span agricultural unit from the straight-line motion in the tracks of PTL in the horizontal plane under the influence of various external disturbances [9, 18].

Sometimes they cause such deviations in different sizes and directions. At the same time, there are the cross deflection, Δx, and yawing rotations $\Delta\varphi$, of the agricultural gantry unit. The nature of external disturbances fully depends on the constructive scheme of the gantry tractor and its technological purpose (soil tillage at a given depth , cultivation of plant sprouts, sowing of different crops, etc.).

Fig. 1. The concepted and manufactured gantry tractor: 1 – frame; 2 – electric motors; 3 – permanent traffic lanes

However, in general, these deviations can be reduced to the following main species: i) cross-displacement of the agricultural unit ($\Delta\varphi = 0$; $\Delta x \neq 0$); ii) yawing deviation of the agricultural unit ($\Delta\varphi \neq 0$; $\Delta x = 0$); iii) yawing deviation along with the transverse offset of the agricultural unit ($\Delta\varphi \neq 0$; $\Delta x \neq 0$) (Fig.2) [24].

C. The mathematical model

On the simplified schematic representation of the manufactured gantry tractor, we shall denote with appropriate letters characteristic points of the tractor in question. It will be: a point S_t – center of mass; L_1 and L_2 – front and rear wheel centres on the left side of the vehicle respectively; R_1 and R_2 – front and rear wheel hubs, starboard respectively; C – the point of connection to the agricultural machine. The gantry tractor under study has transverse and longitudinal symmetry axes, which intersect at the point of S_t form its center of mass (Figure 3). Let us point out on the equivalent scheme the structural parameters of this gantry tractor.

So: K – transverse base (track) of the wide span tractor (distance between the longitudinal axes of the left and right sides); L – its longitudinal base (distance between centers of the front and rear wheels of the left and right sides; b – distance from point C of attachment of the agricultural machine to the longitudinal axis of the left side; l_t – the distance from the centre of the rear wheel on the left and right side of the vehicle to the transverse axis of symmetry of the vehicle passing through its centre of mass (point S_t).

Further, for the analytical description of the plane-parallel motion of an agricultural unit, we will introduce the necessary coordinate systems. Let us first show a stationary Cartesian coordinate system. xOy, rigidly bound to the surface of the field. At the same time, the axle Oy of the specified coordinate system directed towards the progressive motion of the agricultural unit, the axis Ox – to the right as you travel on this axle unit. We accept that the considered agricultural unit, equipped with any agricultural machine, performs on the race relatively fixed horizontal plane. xOy (which is related to the field surface plane) uniform translational motion at a rate of V_0 (Fig. 3).

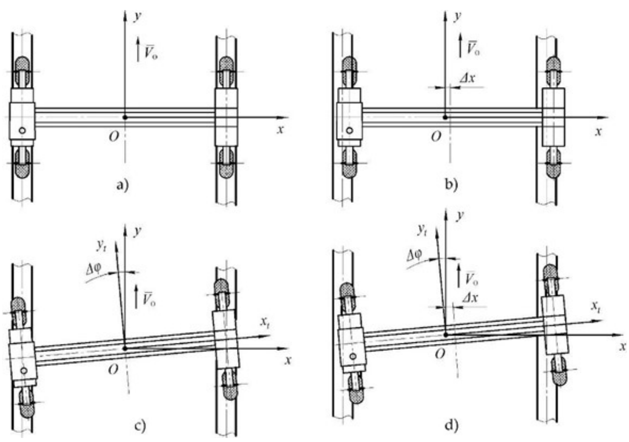

Fig. 2 Schemes of characteristic deviations of a wide span tractor from straight-line motion: a) no deviation, b) cross-displacement of agricultural unit ($\Delta\varphi = 0$; $\Delta x \neq 0$); c) yawing deviation of the agricultural unit ($\Delta\varphi \neq 0$; $\Delta x = 0$); d) yawing deviation along with the transverse offset of the agricultural unit ($\Delta\varphi \neq 0$; $\Delta x \neq 0$)

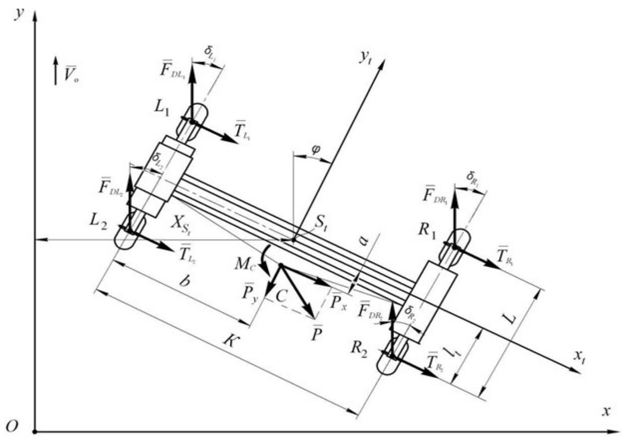

Fig. 3. Equivalent diagram of a bridge agricultural unit with the onboard method of turning in its plane-parallel motion in the horizontal plane.

We will also introduce an additional rectangular Cartesian coordinate system $x_tS_ty_t$, rigidly connected with the agricultural unit, the beginning of which is in its center of mass (point S_t). At the same time, the axis S_ty_t of the given system of coordinates we shall direct along the longitudinal axis of symmetry of agricultural unit, the axis of S_tx_t turn right as he moves along the transverse axis of symmetry of the agricultural unit.

During the agricultural technological process, the axle of the gantry tractor deviates from its original position under the influence of external random disturbances and receives additional speeds.

As a result, a progressive transverse motion of the tractor begins along the *Ox* axis and its rotation around the centre of mass (point S_t) by some angle φ (yawing angle) relative to the coordinate system *xOy* in the horizontal plane. Therefore, the coordinate system mentioned earlier $x_tS_ty_t$ is used to describe the rotation of the agricultural unit around a point S_t on the angle φ on the plane *xOy*, where φ – his yawing angle, namely the angle between the axes *Oy* and S_ty_t (Fig. 2).

In addition, the start of the coordinate system $x_tS_ty_t$ (point S_t), associated with the axle of the gantry tractor, moves in a transverse direction (along the axle of the *Ox*). Position of point S_t at any given time *t* in relation to the axis *Oy* labelled with abscissa X_{St} (Fig. 3). It means that in the process of relative motion of the gantry tractor, its center of mass S_t moves in an axial direction *Ox*, which is characterized by a change in the abscissa X_{St}. This way, the agricultural unit under study with respect to the plane *xOy* has two degrees of freedom to which two generalized coordinates correspond, namely, the angle φ of its turns around the center of mass and the change of the abscissa X_{St} of its center of mass S_t.

External forces acting on the gantry tractor in its plane-parallel motion in the horizontal plane (see Fig. 2) include [25]:

– tangential forces F_{DL_1}, F_{DL_2}, F_{DR_1} and F_{DR_2} of the wheels on the left and starboard sides of the vehicle, attached respectively at the points L_1, L_2 and R_1, R_2, which form, with its longitudinal axis of symmetry, the angles of withdrawal δ_{L_1}, δ_{L_2} and δ_{R_1}, δ_{R_2};

– side forces T_{L_1}, T_{L_2}, T_{R_1} and T_{R_2}, applied respectively at points L_1, L_2 and R_1, R_2;

– attached at point *C* longitudinal P_y and transverse P_x components of traction resistance, as well as the main moment M_C forces acting from agricultural implements.

When the turn is stable, after a series of transformations the following equation is satisfied:

$$J_m \cdot \ddot{\varphi} = \frac{1}{2}K \cdot \left(F_{DL_1} + F_{DL_2} - F_{DR_1} - F_{DR_2}\right) - \frac{1}{2}L \cdot \left\{ \left(k_{L_1} + k_{R_1}\right) \cdot \left[\varphi - \frac{\dot{X}_{S_t} + \frac{1}{2}\sqrt{(L-l_t)^2 + K^2} \cdot \dot{\varphi}}{V_o}\right] - \left(k_{L_2} + k_{R_2}\right) \cdot \left[\varphi - \frac{\dot{X}_{S_t} - \frac{1}{2}\sqrt{{l_t}^2 + K^2} \cdot \dot{\varphi}}{V_o}\right] \right\} - M_C - P_x \cdot a. \quad (1)$$

Equation (1) is a differential equation for the rotation of a gantry tractor around its center of mass (point S_t) in its plane-parallel motion.

Let us further compose the differential equation of transverse displacement of the center of mass of the considered agricultural unit, using the basic law of dynamics, which in this case will be written as follows:

$$M \cdot \ddot{X}_{S_t} = \sum_{k=1}^{n} F_{kx} \quad (2)$$

Where *M* is the mass of gantry tractor; $\ddot{X}_{S_t}$ is the acceleration of the center of mass S_t of agricultural unit in the direction of axis *Ox*; $\sum_{k=1}^{n} F_{kx}$ is the sum of the projections of all external forces acting on the unit in question per axle *Ox*.

Using the equivalent scheme shown in Fig. 3, we can find the sum of the projections of all external forces on the axis of the *Ox*. After performing several transformations, we obtain the sought differential cross-motion equation of the agricultural unit in question, in an axial direction *Ox*.

Combining differential equations (1) and (2) into one system of differential equations, after a series of transformations we obtain the following mathematical model of plane-parallel motion of the skid-steer gantry tractor:

$$\begin{cases} M \cdot \ddot{X}_{S_t} = \left(F_{DL_1} + F_{DR_1}\right) \cdot \left[\dfrac{\dot{X}_{S_t} + \frac{1}{2}\sqrt{L^2 + K^2} \cdot \dot{\varphi}}{V_o}\right] \\ \quad + \left(F_{DL_2} + F_{DR_2}\right) \cdot \left[\dfrac{\dot{X}_{S_t} - \frac{1}{2}\sqrt{L^2 + K^2} \cdot \dot{\varphi}}{V_o}\right] + \\ +2(k_L + k_R) \cdot \left(\varphi - \dfrac{\dot{X}_{S_t}}{V_o}\right) + P_x - P_y \cdot \varphi, \\ J_m \cdot \ddot{\varphi} = \dfrac{1}{2}K \cdot \left(F_{DL_1} + F_{DL_2} - F_{DR_1} - F_{DR_2}\right) \\ \quad + \dfrac{1}{2} \cdot \dfrac{(k_L + k_R) \cdot L^2}{V_o} \cdot \dot{\varphi} - M_C - P_x \cdot a \end{cases} \quad (3)$$

D. The experimental tests

Experimental tests were carried out to statistically assess the variations in terms of yawing angle φ and transversal displacements X_{St} from the trajectory, occurred to the developed agricultural gantry tractor throughout its movement down the tracks of the PTL of 150 m at the speed of 2.0 m s^{-1}. The motion of the unit along these tracks were replicated three times. The yawing angle was determined through the 3-Axis gyroscope module GY-521 (InvenSense Inc, San Jose, California, USA), placed on the frame of the gantry tractor in the vicinity of its centre of mass. The transversal displacements X_{St} from the linearity along the tracks, were metered using a ruler with an accuracy up to 10 mm. The acquired experimental data were statistically handled to estimate the dispersion, frequency, and normalized spectral density (in frequency domain) relating to both the yawing angle φ and the transversal displacements X_{St} [26].

III. RESULTS

A. Numerical solutions

The obtained system of differential equations (3) was numerically solved by us using the parameters of the gantry tractor manufactured by us. Based on the results of the numerical solution, a graph of dependencies of changes in the yawing angle φ and the abscissa X_{St} of the gantry tractor when it performs the skid-steering method of rotation in time t was drawn. (Fig. 4).

From the graphical dependencies presented in Fig. 4 it follows that already for the first 0.6 s from the moment of the created difference of torques brought in the horizontal plane to the wheels of the left and right sides of the gantry tractor its yawing angle φ changes to 6°. And later, this value increases exponentially. But at the same time, it should be considered that after some time of the skid-steer turn the gantry tractor has moved away from the given trajectory and then it is necessary to turn the gantry tractor in the opposite direction for returning to the initial trajectory.

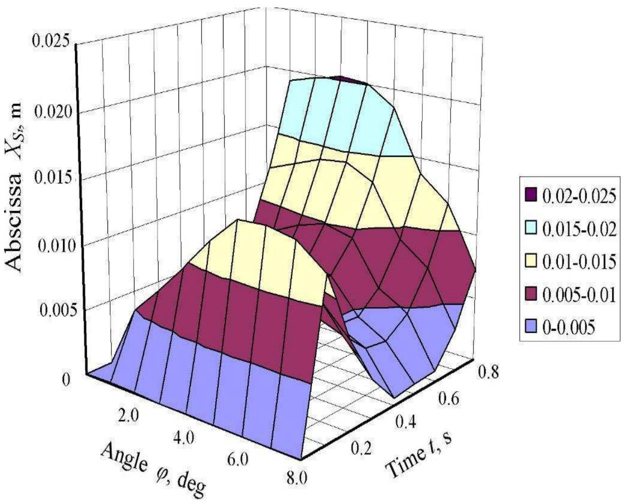

Fig. 4. Schedule of the dependence of changes in the yawing angle φ and the abscissa X_S of the gantry tractor when it performs a skid-steering turnaround in time t.

At the same time, when performing the skid-steer turn of the gantry tractor, the change of abscissa X_{St} is not practically observed (see Fig. 4). It follows that practically the use of skid-steering does not allow solely lateral (plane-parallel) displacements of the longitudinal axis of the gantry tractor. In case of displacement of the gantry tractor's longitudinal axis from the specified trajectory without its turning (for example, due to movement on a cross slope), the restoration of the specified trajectory will be carried out by rotating its longitudinal axis in one direction and subsequently rotating it in the opposite direction.

B. Experimental solutions

The study of the spectral densities points out that throughout the movement of the agricultural gantry tractor along the tracks of the PTL, the fluctuations in connection with either the yawing angle φ and transverse displacements X_{St} were of low frequency and clustered in frequencies range from 0 to 2 s^{-1}, that is from 0 to 0.5 Hz (Fig.5). The standard deviation about the yawing angle has been ±0.014 radians, whereas that one regarding the transverse displacement has been $X_{St} \pm 0.05$ m. These low values of frequency and variance of the fluctuations referred to both the yaw angle and the lateral displacement allow to better organize an automatic control of the steering system of the gantry tractor to align its trajectory to the tracks of the permanent traffic lanes. An automatic guidance system to be mounted on the developed gantry tractor is being studied.

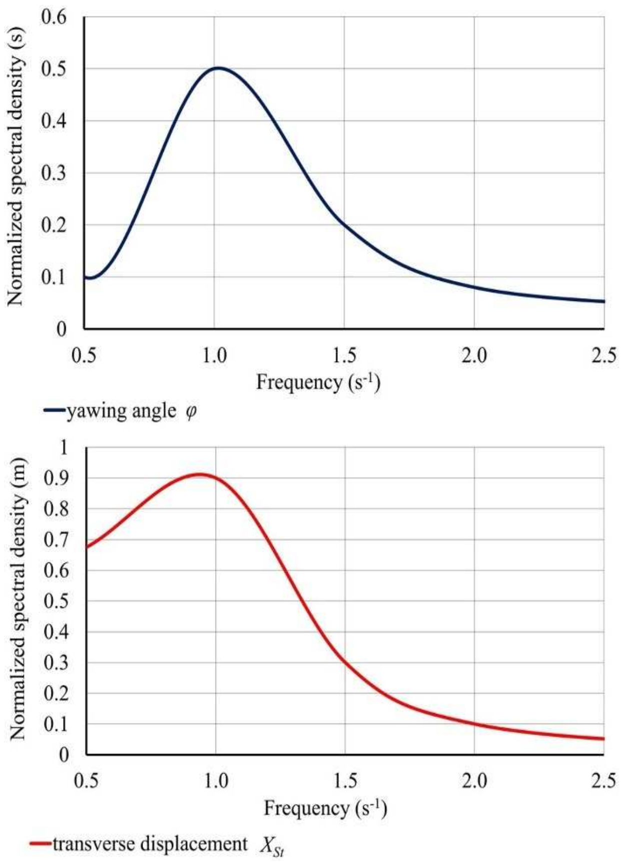

Fig. 5. Normalized spectral densities of the oscillations pertinent either the yawing angle φ and the transverse displacements X_{St}.

IV. Conclusion

The deflections from linear trajectory of a skid-steer gantry tractor conceived and built by the authors, have been analyzed and measured, considering the construction and operational data of this agricultural machine. As a result of the research, it was established that:

- The skid-steering system mounted on the developed gantry tractor allows on average to change the yawing angle φ of 6° in a time of 0.6 s from the time in which the difference between the torques applied to the wheels of the left and right sides of the gantry tractor is produced.
- A rotation of the yaw angle φ in one direction requires a rotation in the opposite directions so that the gantry tractor equipped with skid-system can realign itself to the trajectory marked by the tracks of the permanent traffic lanes.
- If transversal displacements X_{St} of the gantry tractor occur during its motion, the return to the pre-arranged trajectories require successive and consecutive rotations $\Delta\varphi$ of the longitudinal axis of the machine in the two opposite directions.
- The spectral densities pertinent to the fluctuations regarding both the yawing angle φ and transverse displacements X_{St}, which occur during the motion of the gantry tractor along the tracks of the PTL, have been of low frequency (from 0 to 0.5 Hz) as well as very little have been the respective standard deviations of both the operative parameters. All these reduces values allow to arrange an automatic driving system of the gantry tractor.

The study carried out provided useful indications for the development of devices, which should allow to improve the automatic guidance of the studied gantry tractor.

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