Pulsed Nonlinear Automatic Control System for Guidance of a Caterpillar Tractor Unit in Vineyards

Sit M.L.
Institute of Power Engineering
Kishinau, Republic of Moldova

Abstract. The automatic guidance systems of tractors for soil cultivation in vineyards have attracted the attention of researchers since the second half of the twentieth century. The purpose of this paper is to investigate the driving quality of an automatic guidance system (AGS) of a caterpillar tractor unit (CTU) consisting of a crawler tractor and a vineyard plow and having an orientation system for grapes. Compared with the known works (in which GPS, LIDAR, and video cameras are used for orientation), the proposed system is the least expensive. For this, the existence of stability of the AGS as a whole in the range of operating speeds of the unit was proved. The dynamic model of the vineyard plow was verified on a three-point hitching system of the tractor, field tests of the AGS were carried out, which confirmed the results of theoretical studies, and suggested directions for further research. The shape and parameters of the modulation characteristic (MC) of the pulse-width modulator (PWM) of the AGS control system, the rational values of the hydraulic drive speeds of the sequential control mechanism of the clutch of the turn and the crawler tractor belt brake, were established, depending on the slope angle and the speed of the unit, ensuring agrotechnical requirements for driving. New solutions, in comparison with the known ones, are the ways of forming the MC of PWM using a new design probe and the associated driver MC of PWM.

Keywords**:** automatic guidance, caterpillar tractor, pulse-width modulation, control, mechanical probe, field tests.

DOI: **10.5281/zenodo.1217294**

Sistemul neliniar cu impulsuri de dirijare automată pentru conducerea tractorului pe șenile în rânduri ai viței de vie

Șit M.L.
Insitutul de Energetică
Chișinău, Republica Moldova

Sistemele de dirijare automată ale agregatului de tractor pentru prelucrarea solului atrage atenția cercetătorilor din a doua jumătate a secolului al XX-lea. Sarcina lucrărilor conexe acestui domeniu de cercetare – constituie în îmbunătățirea calității conducerii, în reducerea costurilor forței de muncă ale angajaților, în creșterea siguranței personalului la operații de stropire, vărsarea erbicidelor etc. Scopul acestei lucrări este de a studia calitatea sistemului automat de conducere (SAC) a tractorului pe șenile (GTA), constând dintr-un tractor pe șenile și plug pentru prelucrarea solului în rândurile viței de vie și care se orientează la tulpinele plantelor. Comparativ cu lucrări cunoscute (care sunt utilizate pentru orientare GPS, LIDAR, camere video), sistemul propus este low-cost. Pentru aceasta, a fost demonstrată existența stabilității SAC în ansamblu în intervalul vitezelor de funcționare ale agregatului. Au fost stabilite condiții de stabilitate ale sistemului în întregime în diapazonul de viteze și a rezistențelor de tracțiune. Au fost stabiliţi indicii statistici de precizie de mișcare a agregatului. Au fost efectuate încercări în terenuri, care au confirmat rezultatele calculelor teoretice. Au fost stabiliţi forma și parametrii caracteristicii de modulație a PWM (modulația duratei impulsurilor) – modulatorul sistemului de conducere, valorile raționale ale vitezelor acționărilor hidraulice în dependență de condițiile de mișcare a agregatului. Rezultatele noi constau în elaborarea modului de formare a caracteristicii de modulație PWM cu utilizarea sondei de tip nou cu parametrii variabili ai dimensiunilor ale mecanismului sondei, argumentarea teoretică și experimentală a posibilității de conducerea precisă a agregatului de tractor, orientat la butucii viței de vie.

Cuvinte-cheie**:** sistemul de conducere automată, tractorul pe șenile, modulație în durată a impulsurilor, dirijare, sonda mecanică, teste în teren.

Нелинейная импульсная система автоматического управления для вождения гусеничного тракторного агрегата на виноградниках

Шит М.Л.
Институт энергетики
Кишинев, Республика Молдова

Аннотация. Системы автоматического вождения тракторных агрегатов для обработки виноградников привлекают внимание исследователей, начиная со второй половины XX века. Задача работ, связанных этим направлением исследований – повысить качество вождения, снизить затраты на оплату труда работников, повысить безопасность работы персонала при опрыскивании и внесении гербицидов, и т.д. Цель данной работы состоит в исследовании, качества вождения системы автоматического вождения (САВ) почвообрабатывающего гусеничного тракторного агрегата (ГТА), состоящего из гусеничного трактора и виноградникового плуга, и имеющей систему ориентации по штамбам винограда. По сравнению с известными работами (где для ориентации используются GPS, LiDAR, видеокамеры) предлагаемая система является самой малозатратной. Для этого было доказано наличие устойчивости САВ в целом в диапазоне рабочих скоростей агрегата. Также были установлены зависимости точности движения агрегата, в виде среднего отклонения от оси междурядья и дисперсии отклонения от оси междурядья в зависимости от среднего значения и дисперсии разброса осей штамбов относительно оси ряда, определяющей направление движения ГТА в зависимости от скорости движения ГТА и тяговой нагрузки. Также была верифицирована динамическая модель виноградникового плуга на трехточечной навесной системе трактора, проведены полевые испытания САУ САВ, подтвердившие результаты теоретических исследований, а также предложены направления дальнейших исследований. Были установлены форма и параметры модуляционной характеристики (МХ) ШИМ-модулятора системы регулирования САВ, рациональные значения скоростей гидроприводов механизма последовательного управления фрикционной муфтой поворота и ленточным тормозом гусеничного трактора в зависимости от угла склона и скорости движения агрегата, обеспечивающие выполнение агротехнических требований при вождении. Новыми решениями, по сравнению с известными, являются способы формирования МХ ШИМ-регулятора с использованием щупа новой конструкции и связанного с ним формирователя МХ ШИМ.

Ключевые слова: автоматическое вождение, гусеничный трактор, широтно-импульсная модуляция, управление, механический щуп, полевые испытания.

Введение

The work relates to the field of the control of moving objects in agriculture, which is referred to as a “precision agriculture” in the West [18]. A huge number of scientific articles are devoted to this area, scientific conferences are regularly held, European grants are allocated for research. In the field of viticulture, the latest known works are [1-7], which describe vineyard robots for determining the quality of the harvest, its harvesting, as well as automatic aggregates consisting of a wheeled tractor and a sprayer. The accuracy of the automatic driving of these types of machines does not meet the high demands that are imposed on tillers. Therefore, the study of automatic systems for driving such aggregates, in particular, on vineyards is of interest.

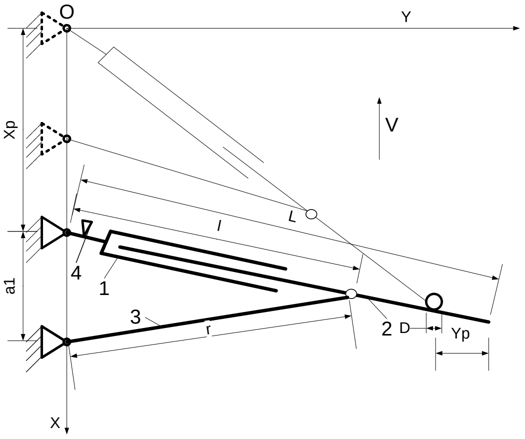
The purpose of this article is the theoretical and experimental justification of the parameters of the regulator of the automatic driving system of a soil-cultivating machine-tractor unit in vineyards using grape stems as landmarks. Scientific works of S.A. Litinsky, A.G. Kechhuashvili [8-9], Yekutieli O. and Garbati-Pegna F. (2002) [13], associated with the development of orientation systems on wire using a low-frequency electromagnetic field generated by electric current in wires or additional wire installed in the lower part of the vine bushes. These systems have not received further distribution due to low reliability. There are known works on orientation systems using mechanical probes for tractors in vineyards of the author of the present article [10, 11, 12] (1978-1985), Upchurch B.L. [14]. There are known works using a laser scanner to calculate the coordinates of straight lines characterizing the rows of grapes, but for vineyards that are clogged with grass, such a system cannot be acceptable. Lifting the sensors above the level of grass height will increase the level of shading from the branches and leaves of grape plants. The system using DGPS [16] can provide the required accuracy of movement due to the high resolution of the GPS (0.02 m) with respect to the required resolution of the orientation system (0.01 m) (in vineyards, the deviations of the agricultural machine from the center of the row must not exceed 0.08 m, while the resolution of GPS is not less than 0.1 m.), and, in addition, the cheapness of the orientation system using probes, in comparison with all other orientation devices is obvious. However, it can be assumed that the optimal technical solution of the orientation system is in the "hybridization" of the mechanical and laser orientation systems. The VINESCOUT 3D optical navigation system from CLEMENS [15], helps the driver in vineyards while driving a tractor and provides an average tractor deviation value of 0.03 m. A number of reviews are devoted to the problem [19-25].

1. Description of the automatic guidance system

The automatic guidance system consists of a hydraulically actuated electrically operated drive which subsequently acts on the pivoting mechanism - friction clutch and belt brake, as well as a controller and an orientation system made in the form of probes and connected to the controller. The probe of the orientation system was made in the form of a rocking mechanism (Fig.1.1).

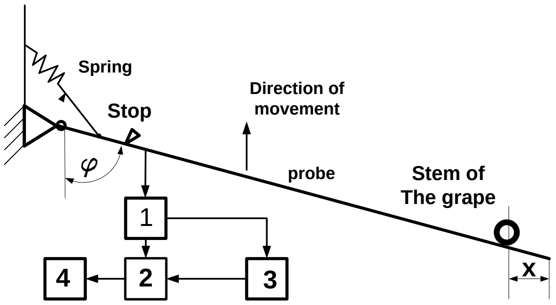
The spring pressing the rocker 1 to the stop 4 is not shown. When this circuit is operated, the probe 2 is pulled out from the slotted bar 1, the value of movement of slotted bar 1 being proportional to the overlapping of the probe by the die. When using this scheme, there is no need for an MTA speed sensor, the calculation algorithm is simpler, the delay for the triggering of the MP, which is inherent in the first version of the VO, is eliminated. Inconvenience is the need to rebuild the lengths of parts a1 and L in the transition from one transmission of the tractor to another. When this circuit is operated, the probe 2 is pulled out of the slotted bar 1, and the amount of movement of the slotted bar 1 is proportional to the overlapping of the probe by the die. In the absence of an electronic circuit for changing the duration of the control pulses, it is necessary to rearrange the lengths of the parts a1 and L when changing from one tractor transmission to another.

If you connect a simple lever probe (Fig.1.2.) With a speed-controlled tractor, a slope angle sensor, a traction resistance sensor with a signal multiplier for the duration of the contact between the probe and the grapes stem (Fig. 1.2), then the need for a stylus with the linkage disappears. The probe has its own turn sensor, which produces a signal, the duration of which is proportional to the contact time of the probe and stem in the "straight" stroke of the probe, when the tractor goes forward and the probe is tilted back. When the contact of the probe and the stem ends and the probe returns to its original position, the signal from the probe's turn sensor does not pass to the controller input, since it disconnects from the controller by the character differentiator included in the system. The character differentiator passes a positive signal from the probe position sensor and disconnects the negative signal from the controller.



1 – Slotted bar, 2-probe, 3 - lever, 4 - probe stop (return spring of the link not shown).

Figure. 1.1. Scheme of the rocking mechanism of the probe movement.



1. Angle meter of the probe. 2. Relay.
3. Differentiator with the signum relay.
4–controller.

Figure.1.2. Lever probe and diagram of its interaction with the controller.

A promising technical solution is that when a bar with sensors is mounted on the probe that allows one to determine what is in front of the sensor: the stem of the grapes or grass. If the sensor has started to deflect, and there is no stem in front of the sensor, only the grass, then the signal of the probe deflection from the reference position does not pass to the regulator.

In Figure 1.3, a photo of a tractor unit with an automatic guidance system is shown.

Let us consider the relationship between the duration of the pulses produced by the lever probe and overlapping by the probe of the plant stem. Due to the fact, that the pulse duration is insufficient effectively influencing the rotation mechanism, it is necessary to increase it, which has been realized in the controller circuit.

$$\tau_i = \left(\sqrt{l^2 - \left(l \sin\varphi - |x_i| \right)^2} - l \cos\varphi + |x| ctg\varphi \right) \Big/ v \quad (1.1)$$

Figure 1.3. Tractor unit with automatic guidance system (AGS) using stems of grapes.

The dependence of the duration of the straight movement of the probe is inversely proportional to the speed of the tractor, depends on the angle of the slope on which the aggregate operates, the height of the probes suspension above the soil surface and depends nonlinearly on the overlapping of the grape's stems by the probes.

$$\tau_i = k \cdot \frac{f(|x_i| \pm h \cdot tg\alpha)}{v} \qquad (1.2)$$

The value of the coefficient «k» in (1.2) is determined by the necessity of realization of stability and precision of movement of the tractor unit with respect to the speed of movement.

2. Investigation of the stability of AGS and statistical indicators of the accuracy of movement of the tractor unit with the AGS by a prescribed trajectory

2.1.1. Mathematical model of a tractor as a control object

As an object of regulation of motion along a prescribed trajectory, a caterpillar tillage tractor unit (CTTU) can be represented as a two-dimensional transfer function with two outputs (trajectory of the tractor center of mass and the center of mass of the vineyard plow), and the single control action - the moment of the tractor turning.

The purpose of this part of the study was to determine the tuning parameters of the regulator, in which the accuracy of driving to agrotechnical requirements is ensured (the coordinate of the center of mass of the tiller is considered as an output).

The desired characteristic of the output process is the standard deviation of the coordinate of the center of the masses of the agricultural machine.

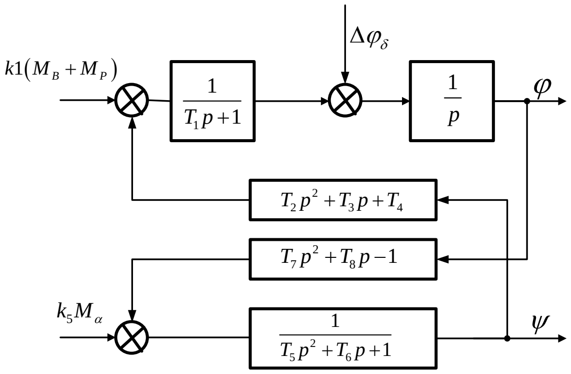


Figure 2.1.1. Transfer function of CTTU, as the object of control of tractor course.

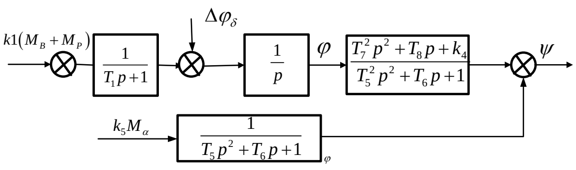


Figure 2.1.2. The simplified block diagram of a tractor unit (consisting of a crawler tractor and a vineyard plow), as a control object in the AGS.

Investigation of the system under the influence of random perturbations

For the research, the method described in [17] has been applied, which consists in determining the linear statistical equivalent of a closed nonlinear system as a whole. The discrete transfer function of the dynamic part of the ACS has the form:

$$W(p) = \frac{k_1' M \left(T_2' p + 1\right) e^{-p\tau}}{p^2 \left(T_1 p + 1\right)} \qquad (2.1)$$

τ – the value of delay in the automatic control system (ACS), T_1 – tractor time constant as the object of control in ACS, $T_2' = R / v$ – the gain of the ACS at the heading angle, R – the shoulder of the edge of the probe in front of the center of mass of the tractor, T – the pulse repetition of PWM $T = L / v$. L – the distance between the stems of plants, v – tractor velocity, M – the turning moment of the tractor, $k_1' = k_1 \cdot v$. Performing the D-transformation of expression (2.1) we obtain equation (2.3).

$$K\left(q\right)=\frac{k_1^{'}M\left(\overline{T}_2^{'}-\overline{T}_1\right)}{e^q-1}+\frac{k_1^{'}MT\left(\left(1-\overline{\tau}\right)e^q+\overline{\tau}\right)}{\left(e^q-1\right)^2}+...$$

$$+\frac{\left(\overline{T}_1-\overline{T}_2^{'}\right)k_1^{'}Me^{-\frac{\tau}{T_\partial}}e^q}{e^q-e^{-\frac{\tau}{T_\partial}}}. \qquad (2.3)$$

It can be demonstrated that the equivalent structural diagram of the ACS has the form (fig.2.1.3).

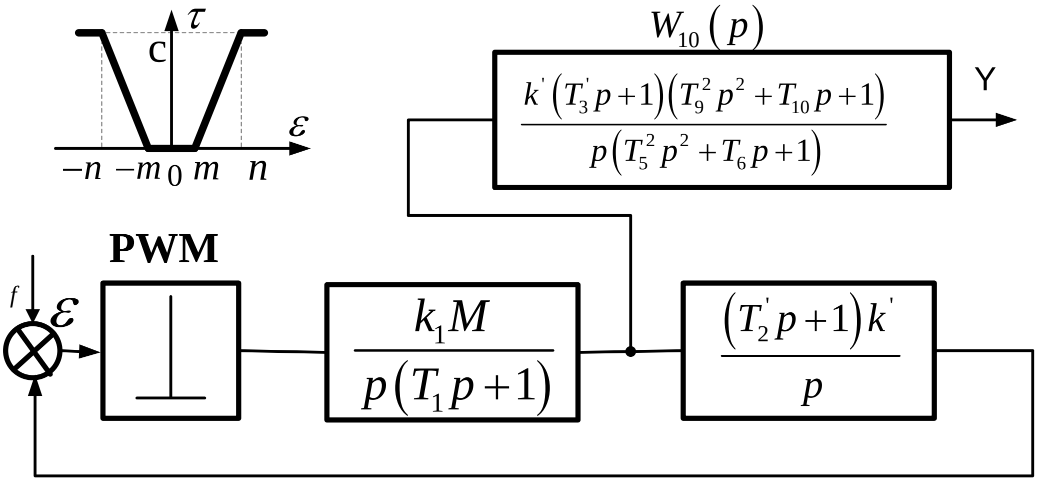


Figure 2.1.3. Simplified block diagram of ACS (upper left graph of PWM modulation characteristic).

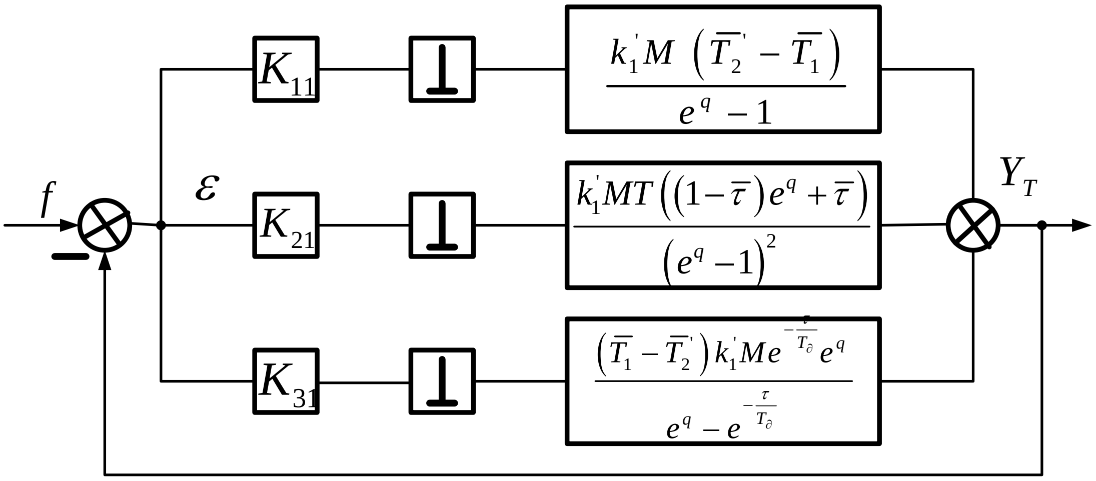


Figure 2.1.4. Equivalent block diagram of ACS.

We represent the response of the linear part of the automatic control system to a sequence of rectangular pulses in the form

$$z\left[nT\right]=\sum_{j=0}^{2}\sum_{m=0}^{n}F_j\left(\left[mT\right]\right)h_j\left(n,m\right), \qquad (2.4)$$

where,

$$F_0(x)=k_1^{'}MT\beta\left(x\right)\Phi\left(x\right)$$
$$F_1(x)=k_1^{'}MT\beta^2\left(x\right)\Phi\left(x\right) \qquad (2.5)$$
$$F_2\left(x\right)=k_1^{'}MT_1\left(1-e^{-\frac{T}{T_1}\beta\left(x\right)}\right)\Phi\left(x\right),$$

where $\beta\left(x\right)$- is PWM modulation characteristics.

We represent the expressions $\Phi_o(x),\left(j=1,2,3\right)$ in the form

$$\Phi_o(x)=\sum_{k=0}^{\mu} C_k^j \cdot H_\nu\left(x\right), \qquad (2.6)$$

where, $H_k\left(x\right)-$ orthonormal Hermite polynomials and C_k^j are equal to [18]

$$C_k^j=\frac{1}{\sigma_x\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{-\frac{(x-\mu)^2}{2\sigma_x^2}}\Phi_j\left(x\right)H_\nu\left(x\right)dx. \qquad (2.7)$$

$$\mu=M\left\{x\right\}.$$

The input process (deviation of the axes of the stems from the row axis) is centered, the amplitude characteristic of the PWM is odd, and then the process of the error signal is centered$\left(C_0^j=0;\mu=0\right)$. We confine ourselves to the first approximation $\nu=1$. Thus, the nonlinear system is replaced by an equivalent linear with coefficients C_1^1, C_1^2, C_1^3 and the statistically linearized model of the automatic control system takes the following form

$$W_L\left(q\right)=\frac{C_1^3\left(\bar{T}_1-\bar{T}_2'\right)k_1'Me^{-\frac{\tau}{T_1}}e^q}{e^q-e^{-\frac{T}{T_1}}}+\frac{C_1^2k_1'M\left(\bar{T}_2'-\bar{T}_1\right)}{e^q-1}+\ldots$$

$$\frac{C_1^1\left(k_1'MT\right)\left(\left(1-\bar{\tau}\right)e^q-\bar{\tau}\right)}{\left(e^q-1\right)^2}. \qquad (2.8)$$

A sign above the elements of the formula means the division of the corresponding quantity by T and reduction to a dimensionless time. The equation for calculating the error signal is as follows:

$$\varepsilon\left(q\right)=\frac{f\left(q\right)}{1+\frac{\sqrt{2}}{b}W_L\left(q\right)}. \qquad (2.9)$$

The equation for calculating the dispersion of the center of gravity of a tillage machine has the following form:

$$\sigma_Y^2\left(\omega\right)=\frac{1}{2\pi}\int_{-\pi}^{\pi} S_1\left(\bar{\omega}\right)\left|W_{10}\left(j\bar{\omega}\right)\right|^2 d\bar{\omega}. \qquad (2.10)$$

$$\bar{\omega}=\omega T.$$

Figure 2.1.5 shows the graphs of the change in the dispersion deviation of the center of masses of the vineyard plow depending on the value of the saturation of the PWM modulation characteristic "c" for various parameters of the control object and the regulator for the disturbance correlation function of the form:

$$R_f\left(\tau\right)=\sigma_f^2\cdot e^{-h\left|\tau\right|}\cdot\cos w\cdot\tau. \qquad (2.6.2)$$

Parameters of the control object, general for the graphs from one to four:

$$T=0.6\,s;T_1=0.1s;\tau=0.2\,s;\sigma_f=0.04\,m.$$

Sets of input data and their corresponding chart numbers are as follows:

1. $k_1'M=0.1c^{-2}m;m_2=0.04\,m;n_2=0.07\,m;\ T_2'=1.5\,s.$
2. $k_1'M=0.2\,c^{-2}m;\ m_2=0.04\,m;n_2=0.07\,m;T_2'=1.0\,s.$
3. $k_1'M=0.3c^{-2}m;m_2=0.02\,m;n_2=0.05\,m;T_2'=1.0\,s.$
4. $k_1'M=0.2\,c^{-2}m;m_2=0.04\,m;n_2=0.07\,m;T_2'=1.0\,s.$

The set of input data (variant 5, fig.2.1.5.).

$$k_1'M=0.96\,c^{-2}m;m_2=0.02\,m;n_2=0.05\,m;T=0.6\,s;T_1=0.31s;$$
$$T_2'=1.5\,s;\ \tau=0.2\,s;\sigma_f=0.05\,m.$$

The graphs are shown in Fig. 2.1.5. From the consideration of the figures, it is seen, that for this system, a "fine" adjustment of the regulator is possible in order to obtain the required characteristics of the system operation, depending on the speed of the tractor unit and its traction load.

From the consideration of the graphs in Figure 2.1.5 it follows that the pulse-width automatic control system can fulfill the agrotechnical requirements.

3. Modeling of indicators of accuracy of process of tractor movement with AGS

The task of statistical digital modeling was to determine the dependence of the main adjusting parameters of the automatic control system: the type of modulation characteristic of the PWM regulator and the speed of the servo rod in order to determine the mathematical expectation and variance of the deviation of the mass center of the plow from the straight line.

Determining the trajectory of the tractor unit for various statistical characteristics of the deviation of the trajectory relative to the middle of the vineyard aisle and when driving at different speeds and with different traction resistance to tractor movement.

The correlation function of the prescribed trajectory has been experimentally determined and approximated by the following expression:

$$R_e(\tau) = D_1 \cdot e^{-h|\tau|} + D_2 \cdot \cos w_1 \cdot \tau. \quad (3.1)$$

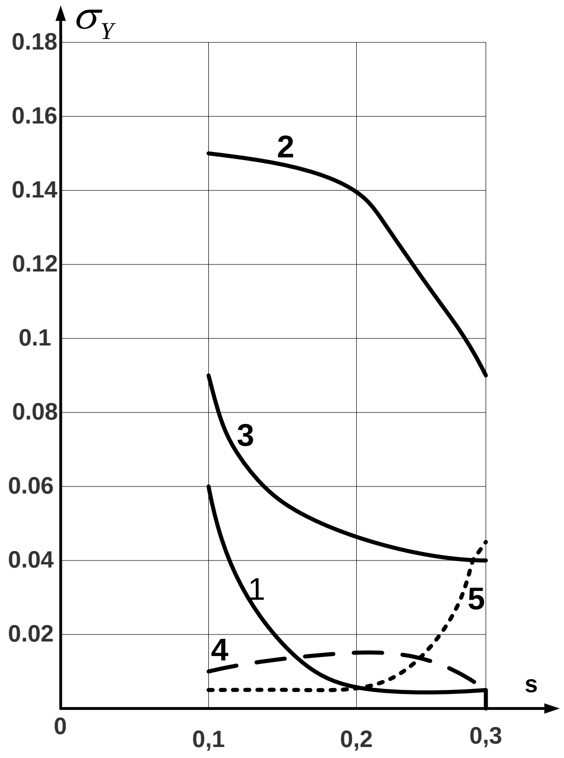


Figure 2.1.5. Dependences of the mean square deviation of the trajectory of the vineyard plow from the parameters of the ACS regulator.

Resulted from the field experiments, the density distribution of the probabilities of the components of the random process of deviations of axes of stems of plants relative to the straight line was estimated and approximated by the expression (3.2):

$$P_{e(1,2)} = \frac{1}{\sqrt{2 \cdot \pi D_{1(2)}}} \cdot \exp\left(-\frac{u^2}{2 \cdot D_{1(2)}} \right). \quad (3.2)$$

As was shown in [103], the first component of the random process $Y_1(t)$, described by the exponential correlation function, has realizations of the following type:

$$Y_1(t) = \lambda_1 \cdot \sin\left(f(\lambda_1) \cdot t + \varphi \right), \quad f\left(\lambda_{1(2)}\right) = -h \quad (3.3)$$

where λ_1 has the Rayleigh distribution law, random initial phase φ distributed uniformly in the interval (0, 2π).

The second component of the random process (3.2) is described by expression

$$Y_2(t) = \lambda_2 \cdot \sin\left(f(\lambda_2) \cdot t + \varphi \right). \quad (3.4)$$

The density of distribution of probabilities $p_{1(2)}(s)$ of variables $\lambda_{1(2)}$ is [103]:

$$p_{1(2)}(s) = \frac{s}{D_{1(2)}} \cdot \exp\left(-\frac{s^2}{2 \cdot D_{Y1(2)}} \right) (3.3)$$

$$f(\lambda) = -h \cdot tg\left[\frac{\pi}{2}\left(1 + \frac{\lambda^2}{2 \cdot D_Y} \right) \exp\left(-\frac{\lambda^2}{D_Y} \right) \right]. (3.4)$$

We define the degree of the polynomial, approximating criteria of system quality of the automatic guidance system $q = 2$. (the integral quadratic criterion is the integral of the square of the deviation of the center of the masses of the tillage trajectory from the straight line characterizing the direction of the row of the vineyard). Then from the formula $N = (1+q)^m$, where $\mathrm{m} = 3$ the number of realizations, characterizing the influence of random perturbations on the precision of the system, will be equal to 27.

Values of statistical nodes μ_{ik_i}, (3.2.3), (3.2.4), will determine the setting on the AGS in the form of random deviations of stems from the straight line. As a result of calculations, the sums

$$M_i = \sum_{i=1}^{N} \rho_{ik} M_{ik_i}; \, D_i = \sum_{i=1}^{N} \rho_{ik} D_{ik_i}; \, , \quad (3.5)$$

where ρ_{ik} – values of Cristoffel numbers of the i – th realization. M_{ik_i}, D_{ik_i} – values of sample mean and variance i – th realization. After carrying out statistical modeling it was established that the AGS is workable, satisfying the agrotechnical requirements to the quality of driving. After that, field tests were required.

4. The field test result of the automatic guidance system

Equation of the AGS reference trajectory $Y_P(I)$, where *I is* the number of the stem in the row, along which the tractor unit moves, orienting itself around the grapes, is as follows:

$$Y_P(I) = \left\| |a_r(i)| - |a_l(i)| \right\| \cdot \\ \cdot sign(\max a_r(i) \vee \max a_l(i)), \quad (4.1)$$

As the results of field experiments have shown, the distribution law of the reference trajectory can be considered normal. Correlation between the deviations of the right and left rows from the straight line is practically absent (the values of the normalized correlation function do not exceed 0.1). If we express the reference trajectory depending on the number of the stem opposite the probe, then the correlation function of the raw will be:

$$R_{xx}(n) = D_1 \cdot e^{-h|n|} + D_2 \cdot \cos w_1 \cdot n, \quad (4.2)$$

where

$$\omega_1 = \frac{2\pi}{(k+1)L_{st}}. \quad (4.3)$$

L_{st} – distance between stems; k – the number of stems per period of a sinusoidal length with a circular frequency ω_1. For the investigated vineyards: $h = 1; k = 5...25; L_{st} = 1.5\,m.$ The sample mean deviation of the rows from the straight line was in the range 0.05 ... 0.08 m, the root-mean-square deviations were 0.05 ... 0.09 m. In the vineyards studied, there was a significant spread of the stems relative to the axis of the row. The quality of guidance of the vineyard tractor unit is determined by the values of the width of the protective zones around the entry points of the grapes bushes into the ground.

Table 1 presents statistics of random processes characterizing the guidance of the unit during the cultivation of the vineyard (tractor T-54B, plow PRVN-2,5A). Let us consider the character of the correlation functions of the input effect (spread of the planting of the vine bushes) for the first variant. From the analysis of these data, it is evident, that the system provides tracking of the average value of the control action. The quality of guidance of the vineyard tractor unit is determined by the width of the protective zones. Let us consider the character of the transformation of the input setting influence (Table 1).

The sample average displacement of the output trajectory is 0.063 m., The right-hand row displacement is 0.061 m, the left - 0.002 m. The comparison of the last two numbers shows the result of the AGS operation - the system provides accurate tracking of the mean value of the control input. The coefficients of amplification of the mean square deviations of the trajectory of the plow, representing the ratio of the variances of the reference trajectory to the trajectory of the plow, are 1.34, 1.16, 1.33 respectively. The values of the asymmetry (A_x) and excess (E_X) coefficients of the output trajectory are less than the same values of the reference trajectory, which positively characterizes the smoothing properties of the AGS.

The values of the asymmetry and kurtosis coefficients for the reference and output trajectories indicate the proximity of the law of distribution of the deviation of the trajectories to the normal one.

The proximity of the normalized correlation and dispersion functions of the trajectories of the center of mass of the plow in the shift zone up to $n = 10$ (the length of the shift along the length is 0.3 m) testifies to the admissibility of using the method of statistical linearization for the investigation of the AGS under random influences. The values of the correlation coefficient of the trajectory of the center of mass of the plow and the protective zones indicate a good quality of tracking by the system of the driving influence.

From the analysis of the correlation functions of the left and right protective zones, determined from the maximum deviation of the stem relative to the axis of the row, it becomes obvious that their correlation coefficients are equal at $n = 0$ when determined as the time of the first intersection by the correlation function of the abscissa axis.

Table 1. Statistics of random processes during automatic and manual guidance of a tractor unit.

Name of the process	m_x [m] 10^{-2}	σ_x [m] 10^{-2}	A_x	E_x
Automatic guidance				
V=2 m/s				
Left row	-0.18	5.48	-0.29	0.24

Right row	6.08	6.34	0.43	-0.24
Reference trajectory	3.39	5.51	0.54	1.52
Right protective zone	18.58	7.68	0.087	-0.34
Left protective zone	26.1	8.6	0.087	0.33
Trajectory of the center of mass of the plow	6.77	7.33	0.38	0.86
V=2.4 m/s				
Left row	-7.1	6.78	-0.34	0.12
Right row	8.14	6.0	-0.047	0.32
Reference trajectory	0.72	8.54	-0.32	-0.68
Right protective zone	28.7	7.7	0.1	0.16
Left protective zone	25.1	9.2	-0.38	0.1
Trajectory of the center of mass of the plow	-0.94	7.17	-0.198	-0.673
V=2.4 m/s, склон 8°				
Left row	-2.73	4.92	0.09	-0.96
Right row	3.76	5.77	-0.59	-0.62
Reference trajectory	1.87	4.06	0.21	-0.77
Right protective zone	29.2	6.36	0.56	-0.12
Left protective zone	16.4	5.62	-0.19	-0.04
Trajectory of the center of mass of the plow	5.55	5.25	-0.678	-0.733
V=1.6 m/s				
Left row	4.13	3.26	0.53	0.59
Right row	0.39	4.21	0.28	-0.32
Reference trajectory	1.82	3.6	-0.66	-1.2
Right protective zone	16.64	8.5	0.34	-0.81
Left protective zone	17.9	6.3	-0.05	-1.04
Trajectory of the center of mass of the plow	2.5	6.12	-0.18	-1.13
Manual guidance V=2.4 m/s				
Right protective zone	10.5…26.4	9.5…10.1	-0.45…-0.92	-0.42…1.3
Left protective zone	16.3…7.5	9.3…11.9	0.73…0.96-	0.025…-0.63
Trajectory of the center of mass of the plow	9.8…14.3	5.6…7.5	0.46…0.42	0.32…-1.1

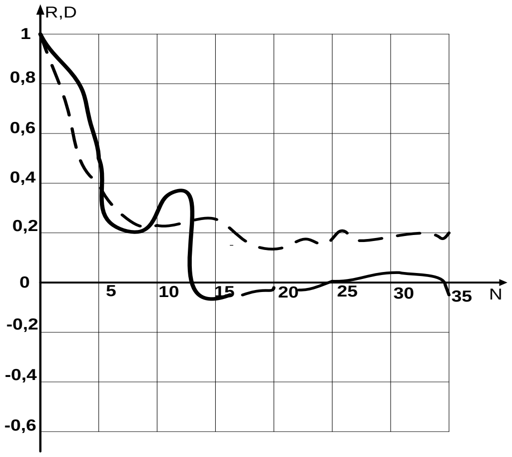


Figure.4.3. **Normalized correlation (R) and dispersion (D) functions of the trajectory of the center of the mass of the plow**.

Analysis of the statistics of the output processes of the AGS operation made it possible to make the following conclusions:

- AGS ensures agrotechnical requirements;
- the average value of the gain factor for the dispersion of the reference trajectory does not exceed 1.3;
- the average value of the protective zone is not less than 0.18 m;
- the average value of the sample mean standard deviation of the protection zone does not exceed 0.068 m;
- the slope time of the correlation function of the trajectory of the center of gravity of the vineyard plow during automatic guidance is less than in the case of manual one, which is explained by the principle of orientation of the AGS.

The time of slope in the correlation functions of the protection zones for automatic driving is 1.4 ... 2.5 times higher than for manual guidance.

Mean square deviations of the trajectory of the central paw of a plow from a straight line for manual and automatic driving differ insignificantly.

Conclusion

1. Analysis of the experimentally obtained statistical characteristics of the automatic driving process showed the absence of auto-oscillations in the automatic control system.
2. For a tractor with a turning mechanism in the form of friction clutches and belt brakes, it is possible to use a relay electrohydraulic drive that ensures their sequential activation, and the braking tape should be tightened by a linearly increasing force as a function of the stroke of the servo rod.

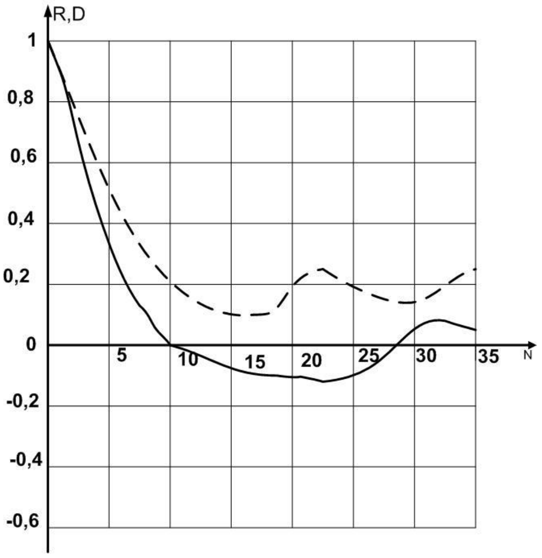


Figure 4.1. Normalized correlation (R, solid line) and dispersion (D, dashed line) function of the right-hand protection zone of the row.

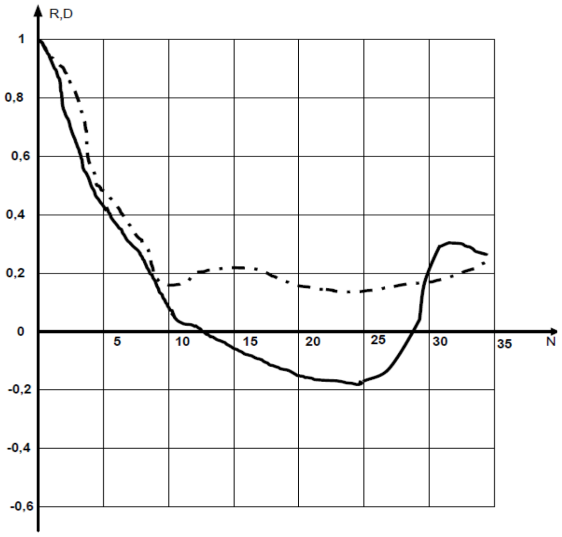


Figure 4.2. Normalized correlation (R, solid line) and dispersion (D, dashed line) function of the left-hand protection zone of the row.

2. When working in vineyards with a distance of more than 1 m between stems, it is necessary to install two pairs of probes with the distance between them being equal to half the distance between the stems.
3. Nonlinear pulsed ACS of AGS of the tractor unit in vineyards ensures carrying out of agrotechnical requirements.
4. Using the probe based on the rocking mechanism allows obtaining control signals with a wide range of variation in duration, depending on the speed of the tractor unit.
5. It has been found that the means of increasing the error-rate performance of the AGS should be the limitation of the duration of the control pulses and the frequency of their repetition.

Литература (References)

[1] VineRobot [homepage on the Internet]. The VineRobot project coordinated by Televitis group, at the University of La Rioja in Spain. Available from: http://www.vinerobot.eu/. (accessed 17.03.2018)

[2] Robotnik [homepage on the Internet]. Valencia: Robotnik Automation SLL Available from: http://www.robotnik.eu/. (accessed 17.03.2018)

[3] Wall-ye softwares and robots [homepage on the Internet]. Available from: http://www.wall-ye.com/. (accessed 17.03. 2018).

[4] Robotics.bgu.ac.il [homepage on the Internet]. The VineGuard project. Available from: http://robotics.bgu.ac.il/index.php/Development_of_an_Autonomous_vineyard_sprayer. Accessed 17.03. 2018.

[5] Vitirover micro winery robotics [homepage on the Internet]. Saint-Emilion: Vitirover. Available from: http://www.vitirover.com/. Accessed 17.03, 2018.

[6] Vision Robotics Corporation [homepage on the Internet]. San Diego, CA: Vision Robotics Corporation (VRC). Available from: http://www.visionrobotics.com/. Accessed 17.03. 2018.

[7] ASI [homepage on the Internet]. Mendon, UT: Autonomous Solutions, Inc. Available from: http://www.asirobots.com/. Accessed 17.03. 2018.

[8] Litinskii S.A. Avtomatizatsia vojdenia samohodnih mashin. M;L.Energia,.[Lirinsky S.A. Automation of driving self-propelled machines], 1966. (In Russian).

[9] Kechhuashvili A.G. Avtomaticeskie ustroistva dlia upravlenia gusenichnymi vinogradnikovymi tratornymi agregatami. [Automatic devices for control of vineyard caterpillar tractor units]. Uchenye zapiski

AzSCHi [Scientific notes of AzSKhI] Kirovobad, 1966, №3 (in Russian).

[10] Sit M.L. Ustroistvo dlia avtomaticheskogo vojdenia traktora na vinogradnikah. [Device for automatic driving of a tractor in vineyards]. Chertificate of the author of the USSR, № 1033034, 1983.(in Russain)

[11] Sit M.L. Obosnovanie strukturi i parametrov sistemy avtomaticheskogo vojdenia tractora na vinogradnikah. [Feasibility of the structure and parameters of the automatic tractor guidance system in vineyards], Issledovania po mechanizatsii vinogradarstva [Research on the mechanization of viticulture], 1985, 170-188.

[12] Sit M.L. Sistema avtomaticheskogo vojdenia tractora na vinogradnikah. [Automatic guiding system of the tractor in vineyards]. Issledovania po mechanizatsii vinogradarstva [Research on the mechanization of viticulture], 1985, 188-195.

[13] Yekutieli O., Garbati-Pegna F. Automatic guidance of a tractor in a vineyard (Paper presented at the Automation Technology for Off-Road Equipment, 2002, Chicago, Illinois

[14] Upchurch B.L., Tennes B.R. and Surbrook T.C. 1983. A microprocessor-based steering controller. Transactions of the ASAE. 26(1): 29-32.

[15] http://www.clemens-online.com/index.EN.php?cnt=p4190 (accessed 17.03.2018)

[16] Longo D., Pennisi A., Bonsignore R., Muscato G., Schillaci G. A Multifunctional Tracked Vehicle Able to Operate in Vineyards Using GPS and Laser Range-finder Technology, *International Conference Ragusa SHWA2010 - September 16-18, 2010 Ragusa Ibla Campus- Italy “Work safety and risk prevention in agro-food and forest systems”*.

[17] Precision Agriculture and Future of Farming in Europe. Technical Horizon Scan. Study. STOA IP/G/STOA/ STOA/FWC-2013-1/Lot 7/SC5. August 2016. European Parliamentary Research Service, European Parliament. DOI: 10.2861/763030.

[18] Tsipkin Ya.Z., Popkov Iu.S. *Teoria nelineinih impulisnih system* [Theory of nolinear pulsed systems], Moskow, 1973, 416p.

[19] Bechar A., Vigneaut C. Agricultural robots for field operations. Part 2: Operations and systems. Biosystems engineering 153(2017), 110-128.

[20] Ming Li, Kenji Imou, Katsuhiro Wakabayashi, Shinya Yokoyama Review of research on agricultural vehicle autonomous guidance. Int J Agric & Biol Eng, 2009; 2(3): 1－16.

[21] Schwarz H-P. and Fischer C. Automatic steering systems used in viticultural tractors. Landtechnik, 2011,N1, 14-17.

[22] Holpp M., Durr L. A. Automatic guidance system for tractors in fruit farming. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjD3pacjcbaAhUnyaYKHZCVAScQFggmMAA&url=https%3A%2F%2Fwww.landtechnik-online.eu%2Fojs-2.4.5%2Findex.php%2Flandtechnik%2Farticle%2Fdownload%2F2011-1-014-017%2F460&usg=AOvVaw103kEEOtkx6PyHxPRpk5KL (accessed 19.04.2018).

[23] Noguchi N., Yang L. Human detection for a robot tractor using omni-directional stereo vision. Computers and Electronics in Agriculture 89 (2012) 116–125.

[24] Cheein F.A., Steiner G., Perez Paina G. and Carelli R. Optimized EIF-SLAM algorithm for precision agriculture mapping based on stems detection. Computers and Electronics in Agriculture 78(2011) 195-207.

[25] Xue Jinlin., Xu Liming Autonomous Agricultural Robot and Its Row Guidance. 2010 International Conference on Measuring Technology and Mechatronics Automation. 725-729, https:// DOI 10.1109/ICMTMA.2010.251.

About the author.

Sit Mikhail Livovichi – PhD., leading researcher, associate Professor – researcher of the Laboratory of Energy Efficiency and Renewable Energy Sources. Area of scientific interests: automatic control of technological processes, robotics.
E-mail: mihail_sit@mail.ru