IMPROVEMENT OF MOVEMENT STABILITY OF TRACTOR-MACHINE UNIT DURING INTER-ROW CULTIVATION OF SUGAR BEET

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Abstract. This study develops and experimentally validates a dynamic model of a tractor-cultivator unit intended for inter-row cultivation of sugar beet and compares two correction concepts: cultivator steered wheels and a controlled lateral hitch. The novelty of the work lies in the combined theoretical and experimental assessment of motion stability for two alternative guidance mechanisms within the same tractor-implement platform by means of transfer functions and logarithmic amplitude-phase-frequency characteristics. The investigated unit consisted of a Class 1.4 wheeled tractor Belarus-1025 and a USMK-5.4B cultivator. The results show that the controlled-hitch configuration provides a wider stability margin than the steered-wheel configuration, with an amplitude range of -40 to -20 dB and a phase shift φ = -7 to -12 deg in the investigated frequency range. Under the tested field conditions, the kinematic safety zone calculated from the measured lateral deviation was 7.6 cm for the unit with steered wheels and 4.8 cm for the unit with a controlled hitch at a speed of 1.56 m·s^{-1}. These values should be interpreted as experimentally obtained kinematic indicators of unit stability. The practical implication is that controlled lateral displacement of the cultivator frame can improve inter-row tracking accuracy and reduce the risk of crop damage in precision and organic cultivation systems.

Keywords: cultivator, tractor, motion stability, controlled hitch, amplitude-phase-frequency characteristic, kinematic safety zone, inter-row cultivation, sugar beet.

Introduction

Reducing damage and cutting of cultivated plants during inter-row cultivation is a critically important task in modern agriculture, particularly in the context of precision farming and organic production, where minimising the use of herbicides is becoming a priority [1-4]. In such systems, the cultivator has to operate as close as possible to the crop row whilst maintaining acceptable agronomic safety.

Three practical guidance approaches are commonly used to improve inter-row cultivation accuracy: manual steering of the tractor, automatic tractor guidance based on GNSS/RTK, and active correction of the implement position relative to the tractor. Camera-guided hoeing, crop-row detection, and side-shift mechanisms have demonstrated substantial potential for reducing deviation from the row centreline [5-9].

One of the key approaches to reducing plant damage is the use of high-precision positioning systems. Global Navigation Satellite Systems (GNSS) combined with Real-Time Kinematic (RTK) technology provide positioning accuracy for agricultural units within a few centimetres, which is critically important for inter-row cultivation [5]. For example, studies have shown that the use of GNSS and autopilot for orientation during planting ensures precise positioning [6]. Such accuracy allows the cultivator working parts to move strictly along the row centres, minimising the risk of damage to crops. However, despite these technologies, damage to individual plants may still occur in some cases, particularly those that deviate significantly from the central axis of the row [7].

Adaptive mechanical systems are being developed and implemented to further reduce plant damage. The “Mriya” electrically driven cultivator has been developed for universal inter-row cultivation of any row crops, offering mechanical loosening as an alternative to chemical methods, particularly for organic farming [8].

Recent vision-based navigation studies have confirmed that robust crop-row detection remains difficult under variable illumination, weed presence, discontinuities and curved rows [6; 9].

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Consequently, high positioning accuracy at the sensor level does not automatically guarantee accurate motion of the cultivator working bodies in the field.

From the standpoint of vehicle dynamics, the lateral displacement of the implement is governed by the coupled motion of the tractor and the mounted cultivator, disturbance rejection, and the method by which the lateral corrective force is transmitted to the soil. Similar conclusions have been reached in studies on tractor-trailer path tracking and articulated agricultural systems [10; 11].

At the same time, relatively few studies analyse the stability of row-crop cultivation specifically from the viewpoint of the tractor-cultivator dynamic system. This aspect remains important because even accurate row detection cannot compensate for insufficient directional stability of the machine-tractor unit [10-13; 17; 18].

In this context, improving the stability of a machine-tractor unit is one way of reducing the kinematic width of the safety zone during inter-row cultivation of row crops, such as sugar beet [16].

Thus, a reduction in plant damage during inter-row cultivation is achieved through the synergistic application of advanced technologies: high-precision positioning, machine vision systems for plant recognition and dynamic correction, as well as adaptive and robotic working bodies, which ensures high weeding efficiency with maximum crop protection [1-3; 6; 7; 15; 19; 20].

Therefore, the objective of this paper is to compare two design solutions for correcting cultivator position relative to the tractor – steered cultivator wheels and a controlled lateral hitch, and to determine which of them provides higher motion stability and lower lateral deviation under field conditions.

Materials and methods

Existing methods of controlling a tractor-mounted unit by acting on the tractor steering wheels do not solve the problem of ensuring a minimum protection zone during inter-row cultivation of sugar beet, since row-crop cultivators (e.g., the USMK-5.4B cultivator) when coupled with a wheeled tractor of a conventional layout (e.g., Class 1.4 tractor Belarus-1025), may deviate laterally by up to 10 cm. In the present study, this 10 cm value is treated as the conventional agronomic benchmark. The smaller values obtained in the experiments are interpreted only as kinematic safety zones of the investigated unit under the tested conditions, not as a replacement of the agronomic requirement.

Possible options for correcting the direction of the cultivator (USMK-5.4B) relative to a Class 1.4 tractor were analyzed for two cases: correction by the cultivator steered wheels and correction by a steered hitch mechanism. The input parameters were field unevenness z, movement resistance Q (disturbing influence) and the steering angle α of rotation of the tractor front steered wheels (control influence). The output variables were the tractor heading angle β and the lateral displacement Δ of the cultivator frame (working body). In Fig. 1, angle β denotes the tractor heading angle.

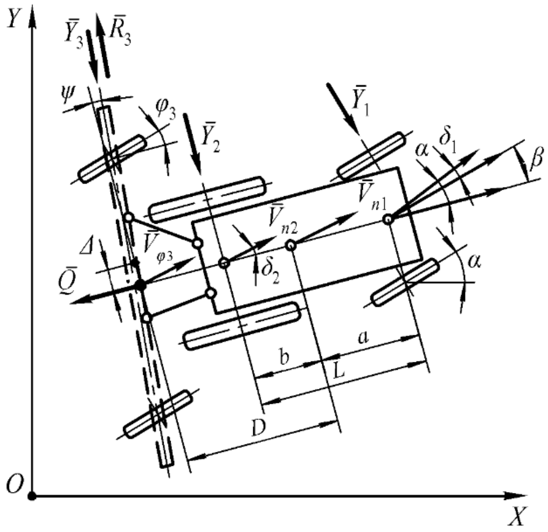

Fig. 1. **Diagram of a machine-tractor unit comprising a wheeled tractor and a mounted cultivator with steered wheels**

When correcting the cultivator's position in the lateral direction (Fig. 1), lateral drift forces act upon it:

$$Y_1 = K_1 \cdot \delta_1 ;\; Y_2 = K_2 \cdot \delta_2 , \tag{1}$$

a force equivalent to the soil reaction on the cultivator during transverse movement

$$Y_3 = K_3 \cdot \dot{y}_k , \tag{2}$$

where K_1, K_2 – coefficients of resistance to lateral drift of the tractor wheels, N·rad^{-1};
K_3 – coefficient of resistance to lateral drift of the cultivator, N·rad^{-1};
$\dot{y}_k$ – cultivator transverse velocity

$$\dot{y}_k = \dot{y} - D \cdot \sin\beta + \Delta \cos\psi \approx \dot{y} - \beta \cdot D + \Delta . \tag{3}$$

The longitudinal displacement of the cultivator is estimated by the force:

$$Q = K_4 \cdot V , \tag{4}$$

where K_4, K_5, K_6 – are lumped coefficients representing, respectively, longitudinal resistance, the soil reaction on the steered cultivator wheels, and the equivalent angular resistance of the cultivator.

For a machine-tractor unit (Fig. 1), the force equivalent to the soil reaction on the cultivator steered wheels in the transverse direction is determined by the steering angle of the cultivator steered wheels φ and the unit speed V:

$$R = K_5 \cdot \varphi \cdot V . \tag{5}$$

The moment equivalent to the pair of soil reaction forces on the cultivator during angular displacement is proportional to the rates of change of the heading angle β and the working body deflection angle ψ:

$$M = K_6 \cdot \left(\beta - \psi\right). \tag{6}$$

When assessing the dynamic properties of a machine-tractor unit comprising a wheeled tractor and a cultivator with steered wheels during inter-row cultivation of row crops, we assume that the unit speed is constant (V = const) and the steering angle of the cultivator steered wheels φ is negligible ($\varphi \leq 5$ deg):

$$Q = \text{const},\; R = K_R \cdot \varphi \;, K_R = K_5 \cdot V . \tag{7}$$

The kinetic energy of the machine-tractor unit will be equal to:

$$T = \frac{1}{2} \cdot \left[m_t \cdot \sqrt{\dot{x}^2 + \dot{y}^2} + m_k \cdot \sqrt{\dot{x}_k^2 + \dot{y}_k^2} + I_t \cdot \dot{\beta}^2 + I_k \cdot \left(\dot{\beta} - \dot{\psi}\right)^2 \right], \tag{8}$$

where m_t, m_k – masses of the tractor and cultivator, kg;
I_t, I_k – moments of inertia of the tractor and cultivator, kg·m^2;
$\psi \approx \Delta / D$ – deflection rotation angle of the cultivator frame relative to the normal position, deg;
Δ – displacement of the cultivator relative to the longitudinal axis of the wheeled tractor, m;
$\dot{x}$, $\dot{y}$ – longitudinal and transverse components of the tractor velocity, m·s^{-1};
$\dot{x}_k$, $\dot{y}_k$ – longitudinal and transverse components of the cultivator working body deflection velocity, m·s^{-1}.

Given the generalised system coordinates y, β and Δ, the force of the cultivator's longitudinal movement is determined by the condition of variability of one of the coordinates and the stability of the others:

$$\delta_y = \text{const} ;\; \delta_\beta = \text{const} ;\; \delta_\Delta = \text{var} ;$$

$$\delta \cdot A_1 = \delta_y \cdot \left[-Y_1 \cdot \cos\left(\beta + \alpha\right) - Y_2 \cdot \cos\beta - Y_3 \cdot \cos\left(\beta - \psi\right) - Q \cdot \sin\beta + R \cdot \cos\left(\beta + \psi\right) \right]; \tag{9}$$

$$Q_1 = -Y_1 - Y_2 - Y_3 - Q_\beta + R\,. \tag{10}$$

$$\delta_y = \text{const}\,;\ \delta_\beta = \text{var}\,;\ \delta_\Delta = \text{const}\,;$$

$$\delta_{\Delta 2} = \delta \cdot \beta \cdot \left[-Y_1 \cdot a \cdot \cos\alpha + Y_2 \cdot b + Y_3 \cdot D \cdot \cos\psi - R \cdot D \cdot \cos\psi + M + \Delta \cdot Q\right]; \tag{11}$$

$$Q_2 = -Y_1 \cdot a + Y \cdot b + Y_3 \cdot D - R \cdot D + M + \Delta \cdot Q\,. \tag{12}$$

$$\delta_y = \text{const}\,;\ \delta_\beta = \text{const}\,;\ \delta_\Delta = \text{var}\,;$$

$$\delta_{\Delta 3} = \delta_\Delta \cdot \left[R - Y_3\right] \cdot \cos\psi\,. \tag{13}$$

The controllability of the object is assessed by a differential equation obtained by differentiating the partial derivative of the kinetic energy *T*, defined by expression (8), with respect to the rate of change of the generalised coordinates: *y*, *β* and Δ. The resulting system was further transformed in the Laplace domain to obtain the transfer functions used for stability analysis. We have:

$$\left.\begin{array}{l} y(S)A_1(S) - \beta(S)B_1(S) + \Delta(S)C_1(S) = \alpha(S)K_1 + \varphi(S)K_2; \\ -y(S)A_2(S) + \beta(S)B_2(S) - \Delta(S)C_2(S) = \alpha(S)K_1 a - \varphi(S)K_2 D; \\ y(S)A_3(S) - \beta(S)B_3(S) + \Delta(S)C_3(S). \end{array}\right\}, \tag{14}$$

where S – Laplace operator, s^{-1};

$A_1(S)\ldots A_3(S)$ – inertial-damping polynomials of lateral motion;

$B_1(S)\ldots B_3(S)$ – describe the angular (yaw) motion;

$C_1(S)\ldots C_3(S)$ – describe the coupling between lateral displacement and cultivator shift.

$$A_1(S) = S\left[Sm_\kappa + \left(\frac{K_1 + K_2}{V} + K_3\right)\right]; \tag{15}$$

$$A_2(S) = S\left[Sm_k D + \left(K_3 D + \frac{K_2 b - K_1 a}{V}\right)\right]; \tag{16}$$

$$A_3(S) = S\left[Sm_\kappa + K_3\right]; \tag{17}$$

$$B_1(S) = S\left[SDm_\kappa + \left(K_3 D + \frac{K_2 b - K_1 a}{V}\right)\right] + K_1 + K_2 - Q\,; \tag{18}$$

$$B_2(S) = S\left[S\left(m_\kappa D^2 + I_\kappa\right) + \left(\frac{K_1 a^2 + K_2 b^2}{V} + K_3 D^2 - K_6\right)\right] + K_2 b - K_1 a\,; \tag{19}$$

$$B_3(S) = S\left[S\left(m_\kappa D + I_\kappa / D\right) + K_3 D\right]\,; \tag{20}$$

$$C_1(S) = S\left(m_\kappa + K_3\right). \tag{21}$$

From the system of equations (5) we obtain:

$$\begin{gathered} D(S) = A_1(S)B_2(S)C_3(S) + B_1(S)C_3(S)A_3(S) + A_2(S)B_3(S)C_1(S) - \\ -A_3(S)B_2(S)C_1(S) - A_1(S)C_2(S)B_3(S) - A_2(S)B_1(S)C_3(S); \end{gathered} \tag{22}$$

$$\begin{gathered} D_y^2(S) = B_2(S)C_3(S)K_1 - B_3(S)C_1(S)K_1 a + B_1(S)C_3(S)K_1 a - \\ -B_3(S)C_2(S)K_1: \end{gathered} \tag{23}$$

$$\begin{gathered} D_y^\varphi(S) = B_2(S)C_3(S)K_R + B_1(S)C_2(S)K_R + B_3(S)C_1(S)K_R D - \\ -B_2(S)C_1(S)K_R - B_3(S)C_2(S)K_R - B_1(S)C_3(S)K_R D; \end{gathered} \tag{24}$$

$$\begin{gathered} D_3^2(S) = A_1(S)C_3(S)K_1a - A_3(S)C_2(S)K_1 - A_3(S)C_1(S)K_1a + \\ + A_2(S)C_3(S)K_1; \end{gathered} \tag{25}$$

$$\begin{gathered} D_\beta^\varphi(S) = -A_1(S)C_3(S)K_RD - A_3(S)C_2(S)K_R - A_2(S)C_1(S)K_R + \\ + A_3(S)C_1(S)K_RD + A_1(S)C_2(S)K_R + A_2(S)C_3(S)K_R; \end{gathered} \tag{26}$$

$$\begin{gathered} D_\Delta^\alpha(S) = -A_3(S)B_1(S)K_1a + A_2(S)B_3(S)K_1 - A_3(S)B_2(S)K_1 + \\ + A_1(S)B_3(S)K_1a; \end{gathered} \tag{27}$$

$$\begin{gathered} D_\Delta^\varphi(S) = A_1(S)B_2(S)K_R + A_3(S)B_1(S)K_RD + A_2(S)B_3(S)K_R - \\ - A_3(S)B_2(S)K_R - A_2(S)B_1(S)K_R - A_1(S)B_3(S)K_RD. \end{gathered} \tag{28}$$

Taking these polynomials into account, we rewrite the system of equations (14) as:

$$\left.\begin{aligned} y(S)D(S) &= \alpha(S)D_y^\alpha(S) + \varphi(S)D_y^\varphi(S); \\ B(S)D(S) &= \alpha(S)D_\beta^\alpha(S) + \varphi(S)D_\beta^\varphi(S); \\ \Delta(S)D(S) &= \alpha(S)D_\Delta^\alpha(S) + \varphi(S)D_\Delta^\varphi(S). \end{aligned}\right\} \tag{29}$$

From this system of equations, we obtain the transfer functions of the machine-tractor unit (Class 1.4 wheeled tractor + cultivator with steered wheels), which characterise the response of the lateral displacement Δ in terms of the steering parameters of the tractor α and the cultivator φ:

$$W_\Delta^\alpha(S) = \frac{D_\Delta^\alpha(S)}{D(S)}; \; W_\Delta^\varphi(S) = \frac{D_\Delta^\varphi(S)}{D(S)}. \tag{30}$$

An analysis of the dynamic properties of this machine-tractor unit was carried out for the following forward speeds: $V_1 = 1.56$ m·s^{-1}, $V_2 = 1.85$ m·s^{-1}, $V_3 = 2.17$ m·s^{-1}.

For the theoretical investigations, the following parameters of this machine-tractor unit were adopted: $m_t = 3544$ kg, $m_k = 870$ kg, $I_t = 4260$ kg·m^2, $I_t = 2152$ kg·m^2, $K_1 = 0.1 \cdot 10^5$ N·rad^{-1}, $K_2 = 0.3 \cdot 10^5$ N·rad^{-1}, $K_3 = 0.7 \cdot 10^5$ N·rad^{-1}, $K_4 = 0.5 \cdot 10^2$ N·rad^{-1}, $Q = 10500$ N, $a = 1.365$ m, $b = 1.005$ m, $L = 2.37$ m, $D = 2.14$ m.

These values and units are provided explicitly to facilitate interpretation of the model.

A series of experimental studies was conducted to verify the adequacy of the mathematical model describing the dynamics of this tractor-implement unit and to quantify the dispersion of lateral deviation used for safety-zone calculation.

A Class 1.4 tractor and a USMK-5.4B cultivator were used in field trials of the prototype automatic driving system. The comparison was carried out for two configurations:

- the USMK-5.4B cultivator equipped with steered wheels, allowing correction of the direction of travel by lateral displacement of the cultivator frame;
- the USMK-5.4B cultivator equipped with a controlled hitch, allowing the cultivator frame to be shifted laterally relative to the tractor frame.

During the experimental studies, the measurement system for the dynamics and energetics of mobile machines described in [12-15] was used. The system synchronously recorded the forward speed V, the tractor heading angle β, and the lateral displacement Δ of the cultivator relative to the tractor's longitudinal axis. The recorded time histories were used to construct the logarithmic amplitude-phase-frequency characteristics and to estimate the variance of lateral deviation. The kinematic safety zone was calculated as $\Delta_s = 3\sigma$ and the full safety zone width as $Z_s = 2\Delta_s = 6\sigma$, where σ was obtained from the sample variance of lateral deviation. The movement of the machine-tractor unit, equipped with a mock-up of an automatic driving system, was carried out along the furrows formed during sugar beet sowing.

Results and discussion

Fig. 2 compares the theoretical and experimental logarithmic amplitude-frequency and phase-frequency characteristics of the investigated machine-tractor units.

Logarithmic amplitude-phase frequency characteristics make it possible to estimate the magnitude of the phase shift, which determines the control margin in a closed-loop control system. The machine-tractor unit comprising a Class 1.4 wheeled tractor and a USMK-5.4B cultivator with a controlled hitch has a distinct advantage over the variant of the cultivator with controlled wheels, as its amplitude is: -40…-20 dB, and the phase φ = -7…-12 deg (Fig. 2).

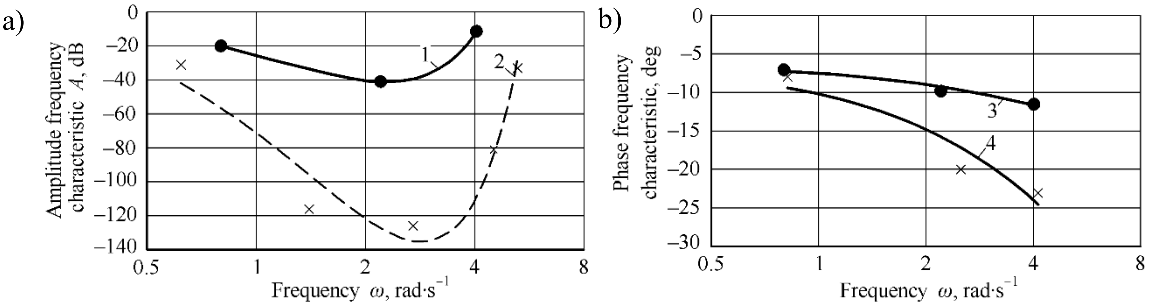

Fig. 2. **Logarithmic amplitude-frequency (a) and phase-frequency (b) characteristics of the machine-tractor unit on the base of Class 1.4 tractor:** ● – USMK-5.4B with controlled hitch (experimental): —— –USMK-5.4B with controlled hitch (theoretical); × – USMK-5.4B with steered wheels (experimental); – – – USMK-5.4B with steered wheels (theoretical)

This behaviour is explained by the fact that, in the controlled-hitch configuration, the force required for the lateral correction of the cultivator is transmitted to the soil through the tractor running system. In practical terms, this principle is consistent with precision hoeing studies showing the benefit of active implement correction and guidance systems for keeping the working bodies closer to the crop row [5; 7-9].

Table 1

Test results for the machine-tractor unit and calculated dispersion parameters

Machine-tractor unit	σ^2_{n-1}, (cm^2)	$\Delta = 3\sigma$, (cm)
Class 1.4 wheeled tractor + USMK-5.4B with controlled hitch	0.61	2.328
Class 1.4 wheeled tractor + USMK-5.4B with steered wheels	1.642	3.844

The use of a cultivator with a controlled hitch allows the cultivator frame to be moved relative to the tractor frame, enabling higher-quality inter-row cultivation of sugar beet and reducing the risk of damage to crops in the row (Table 1). For the investigated forward speed of 1.56 m·s^{-1}, the experimentally obtained standard deviations correspond to kinematic safety zones $Z_s = 6\sigma$ of 7.6 cm for the unit with steered wheels and 4.8 cm for the unit with a controlled hitch. These values describe the stability-related kinematic capability of the unit under the tested conditions. They should not be interpreted as replacing the conventional 10 cm agronomic protective zone, because the biological admissibility of a narrower zone depends on crop stage, field conditions, and separate agronomic validation.

Conclusions

1. It has been established that the motion stability of the tractor-cultivator unit is a decisive factor affecting the accuracy of inter-row cultivation of sugar beet. The developed mathematical model and the experimental data confirmed that the method of lateral correction directly influenced the deviation of the cultivator working bodies from the row centreline.
2. Logarithmic amplitude-phase frequency characteristics made it possible to evaluate the magnitude of the phase shift, which determines the stability margin in a closed-loop control system. The machine-tractor unit comprising a Class 1.4 wheeled tractor (Belarus-1025) and a USMK-5.4B cultivator with a controlled hitch has a clear advantage over the configuration with steered cultivator wheels, because its amplitude lies within -40 to -20 dB and its phase shift φ = -7 to -12 deg. This is

because the force required for the lateral displacement of the cultivator with a steered hitch is transmitted to the soil via the tractor.

3. Under the tested field conditions and at a speed of 1.56 $m \cdot s^{-1}$, the experimentally obtained kinematic safety zone was 7.6 cm for the machine-tractor unit with steered cultivator wheels and 4.8 cm for the unit with a controlled hitch. These values should be considered engineering indicators of motion accuracy rather than revised agronomic norms. Verification of the biological admissibility of reduced protective zones for different growth stages of sugar beet should be the subject of further agronomic research.

Author contributions:

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

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