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DOI: 10.2478/ata-2024-0006

Acta Technologica Agriculturae 1
Nitra, Slovaca Universitas Agriculturae Nitriae, 2024, pp. 35–42

JUSTIFICATION OF THE UNIT DESIGN DIAGRAM FOR MOWING AGRICULTURAL CROPS SIMULTANEOUSLY WITH THEIR STUBLE CHOPPING

Pavol FINDURA[1]*, Volodymyr NADYKTO[2], Volodymyr KYURCHEV[2], Jakub MANKOVECKÝ[3]

[1]Slovak University of Agriculture in Nitra, Faculty of Engineering, Institute of Agricultural Engineering, Transport and Bioenergetics, Nitra, Slovak Republic
[2]Dmytro Motornyi Tavria State Agrotechnological University, Mechanical and Technological Faculty, Department of Machine Usage in Agriculture, Melitopol, Ukraine, volodymyr.nadykto@tsatu.edu.ua (V.N.), volodymyr.kyurchev@tsatu.edu.ua (V.K.)
[3]Slovak University of Agriculture in Nitra, Faculty of Horticulture and Landscape Engineering, Institute of Horticulture, jakub.mankovecky@uniag.sk
*correspondence: pavol.findura@uniag.sk

The two-phase method is quite widespread when harvesting grain crops and forage grasses. For its implementation, farmers prefer harvesting units with a front-mounted header. The main disadvantage of such units is that after their passage in the space between the swaths of mown crops, open soil falls under the direct influence of sunlight. Subsequently, this leads to an intensive loss of its moisture. A harvesting unit has been designed to eliminate this shortcoming, consisting of a tractor with a front harvester and a soil-cultivating machine (disc harrow) mounted at the rear. The latter chops stubble and soil in the space between the swaths of the mowed crop, contributing to soil moisture conservation. In the diagram plan, the tillage machine can have a swivel or fixed conjunction with the tractor in a horizontal plane. A mathematical model of the harvesting unit plane-parallel movement in the horizontal plane has been designed to choose these conjunctions better. In the study, it is used to analyze the corresponding amplitude (AFC) and phase (PFC) frequency characteristics of a dynamic system when it is working out a control action in the form of the sighting point transverse shift. As a mathematical modeling result, it was found that the fixed conjunction of a tillage machine with a tractor is preferable. In this case, the natural AFC practically approaches the perfect one for servo dynamical systems. The correlation degree between the tractor's steered wheels' rotation and heading angles increases by almost 37%. As a result, this leads to a significant decrease in this parameter variance fluctuations, which contributes to an increase in the harvesting unit controllability movement as a whole.

Keywords: header; two-phase harvesting method; amplitude frequency characteristic; phase frequency characteristic; normalized spectral density

Despite the widespread use in the world of the one-phase method of harvesting crops, in many countries, the two-phase method is in demand. Each of them is determined by the advantages of its implementation in a particularly natural and climatic zone (Chongyou et al., 2014; Rudoy et al., 2021).

It should be emphasized that the two-phase method of harvesting is standard, not only when mowing cereal crops. It is widely used in forage grass and rape harvesting. For this, trailed and mounted harvesting units are used. The formers are designed based on a tractor and a trailed windrower located to its right (Bulgakov et al., 2018a; Kollárová et al., 2014, Konstantinov et al., 2019; Undersander et al., 2011). Since such a unit is asymmetric, it has problems with movement stability in the horizontal plane. Quite often, this negatively affects not only the harvesting unit's movement trajectory indicators but also the quality of its operation (Bulgakov et al., 2019, 2018b).

Mounted harvesting units are equipped with front headers. If they form a swath in the used self-propelled vehicle track area, they are usually symmetrical (Caixia et al., 2015; Foster et al., 2005; Gesce, 2004; Jin et al., 2022). If the swath is formed to the left or right of the front-mounted header, then the latter is attached to the self-propelled vehicle asymmetrically (Li et al., 2021; Rudoy et al., 2021; Shinners et al., 2012). However, its transverse displacement is so small that it usually does not cause problems with horizontal plane's harvesting unit plane-parallel movement stability.

After mowing an agricultural crop into a swath, its stubble remains on the field. To avoid moisture loss and weed control, it must be quickly chopped by tillage with disc cultivators or harrows. As the results of studies have shown, the timely implementation of this essential technological operation makes it possible to ensure moisture conservation in the soil up to 2–6 mm (Tsibulka et al., 2005).

However, at the moment, there are no units that would mow crops into a swath and at the same time chop their stubble. Attempts to implement this specialized technique with a unit consisting of a harvester and a trailed cultivator (Maslov et al., 2010) were unsuccessful. This outcome is because a trailed tillage machine significantly complicates the movement of the harvesting unit in reverse when manoeuvring on the headland. Theoretically, the nature of such dynamic system movement has not been studied, which is why neither its diagram nor design parameters are substantiated.

Manoeuvring a similar harvesting unit can be satisfactorily solved using a mounted soil-cultivating machine – a harrow or a cultivator. At the same time, if the front harvester must have only a fixed one, then a harrow or a cultivator can have both a fixed and swivel conjunction in the horizontal plane with a self-propelled device.

In the case of a fixed conjunction of the soil tillage machine with the self-propelled vehicle, the problem of harvesting unit movement controllability may arise in principle. For its theoretical evaluation, an appropriate mathematical apparatus is needed. Since at the moment it does not exist, the aim of this article is:

1. to design a mathematical model that reflects the control action influence on the functioning nature of a dynamic system as part of a self-propelled vehicle with a front-mounted header and a rear-mounted soil-cultivating machine;
2. substantiation of the harvesting unit design diagram by assessing the controllability of its plane-parallel movement in the horizontal plane.

Material and methods

Methodology for theoretical research of a harvesting unit

Under the "design diagram of the harvesting unit" concept, we mean a fixed or swivel conjunction method of a self-propelled vehicle with a tillage machine in a horizontal plane. As a self-propelled vehicle, consider a tractor with front steerable wheels equipped with rear and front three-point hitch linkages. The fixed conjunction of the tractor with the soil-cultivating machine in the horizontal plane is provided by fixing the lower links of its rear hitch linkage with checking chains. In the case of a swivel conjunction between the machine and the tractor, these chains are lengthened so that the lower links of the hitch linkage, together with the mounted soil-cultivating machine, can rotate relative to the tractor by about ±8°.

First of all, let's consider a more general harvesting unit diagram with swivel conjunction of a tillage machine (disk harrow) to a tractor (Fig. 1). In the process of moving at a constant speed V_o, the unit, under the influence of random factors, rotates in the *YOX* plane by an angle φ around the vertical axis that passes through the tractor and header mass centre (point *S*). This point, in turn, moves along the *OX* axis, corresponding to a change in the abscissa $X_s = OS$. As a result, the soil-cultivating machine, swivelly in conjunction with the tractor, makes its independent angular movements, the measure of which is the angle β.

The considered unit as a dynamic system in the *YOX* plane has three degrees of freedom, which correspond to three generalized coordinates: the abscissa X_s and the angles φ and β. The following external forces form their change: the longitudinal (R_k, kN) and transverse (R_p, kN) components of header traction resistance applied in point *C*; gross traction (F_b, kN), applied in point *B* and forming their yaw angle δ_b (rad); tractor's driven wheels rolling resistance (P_{fa}, kN), applied in point *A* and forming their yaw angle δ_a (rad); lateral forces T_a, T_b and T_k (kN), applied in points *A*, *B* and *K*; disc harrow resistance force P_r (kN), applied in point *M* and deviated from the tractor's longitudinal axis by angle β; the rolling resistance force of the disc harrow wheels P_{fk}, applied in point *K* and deflected by the yaw angle of these wheels tires δ_k.

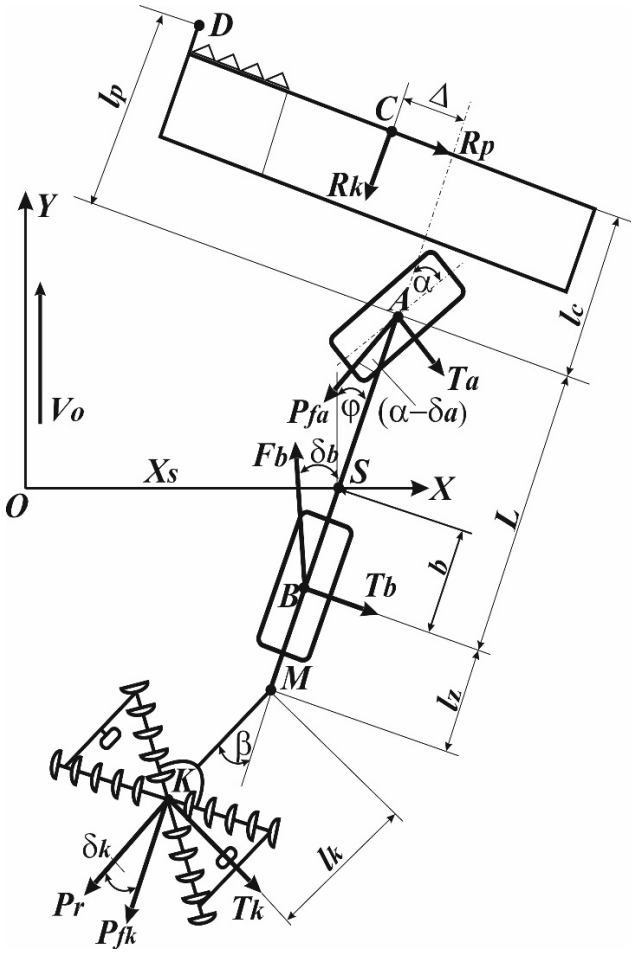


Fig. 1 Harvesting unit diagram with the swivel junction of a tillage machine

In the operator form of the record, the mathematical model of the horizontal movement of the considered harvesting unit has the following format:

$$\begin{aligned} K_{11} \cdot X_s(p) + K_{12} \cdot \varphi(p) + K_{13} \cdot \beta(p) &= F_{11} \cdot \alpha(p) + F_{12} \cdot R_p(p) \\ (K_{21} \cdot X_s(p) + K_{22} \cdot \varphi(p) + K_{23} \cdot \beta(p) &= F_{21} \cdot \alpha(p) + F_{22} \cdot f_{22}\,(p) \quad (1) \\ K_{31} \cdot X_s(p) + K_{32} \cdot \varphi(p) + K_{33} \cdot \beta(p) &= F_{31} \cdot \alpha(p) \end{aligned}$$

where:

$K_{11} = A_{11} \cdot p^2 + A_{12} \cdot \mathrm{p}$
$K_{12} = A_{13} \cdot p + A_{14}$
$K_{13} = A_{15}$

$K_{21} = A_{24} \cdot p$
$K_{22} = A_{21} \cdot \mathrm{p}^2 + A_{22} \cdot \mathrm{p} + A_{23}$
$K_{23} = A_{25}$
$K_{31} = A_{36} \cdot p$

$A_{11} = M_a$
$A_{12} = (k_a + k_b + P_{fa} - \mathrm{Fb}) \cdot V_o^{-1}$
$A_{13} = \left[(k_a + P_{fa})(L - \mathrm{b}) + (F_b - k_b)b\right] V_o^{-1}$
$A_{14} = -A_{12} \cdot V_o$
$A_{15} = P_r$
$A_{21} = J_a$
$A_{22} = \left[(k_a + P_{fa})(L - \mathrm{b})^2 + (k_b - F_b)\, b^2\right] V_o^{-1}$

$K_{32} = A_{34} \cdot p + A_{35}$
$K_{33} = A_{31} \cdot p^2 + A_{32} \cdot p + A_{33}$
$F_{11} = f_{11} = k_a$
$F_{12} = F_{22} = 1$
$f_{12} = R_p$
$F_{21} = f_{21} = (L - b) \cdot k_a$
$f_{22} = R_p(b + l_c) - Rk \cdot \Delta$
$F_{31} = 0$
$A_{35} = A_{33}$
$p = d/dt$ – laplace operator

$A_{23} = -A_{13} \cdot V_o$
$A_{24} = A_{13}$
$A_{25} = -P_r(b + l_z)$
$A_{31} = J_m$
$A_{32} = (k_k + P_{fk}) \cdot l_k^2 \cdot V_o^{-1}$
$A_{33} = (k_k + P_{fk}) \cdot l_k$
$A_{34} = (k_k + P_{fk}) \cdot (L - b + l_z) \cdot l_k \cdot V_o^{-1}$
$A_{36} = -A_{33} \cdot V_o^{-1}$

Equations system (1) includes the following parameters: M_a is the mass of the tractor with a mounted header, kg; J_a is the tractor and header inertia moment relative to the vertical axis passing through point S (see Fig. 1), kg·m^2; J_m is the disk harrow inertia moment about the axis passing through point M, kg·m^2; k_a, k_b, k_k are the coefficients of resistance to tire yaw of the tractor front and rear wheels, as well as the wheels of the disc harrow, respectively, kN·rad^{-1}; L, b, Δ, l_c, l_z, l_k are the linear design parameters of the unit (Fig. 1).
The input variables in the equations system (1) are:

1. the control action in the form of tractor's steered wheels rotation angle (α);
2. disturbing action from the force R_p;
3. the total disturbing effect represented by the factor f_{22}. Its components are disturbing moments $R_p \cdot (b + l_c)$ and $R_k \cdot \Delta$.

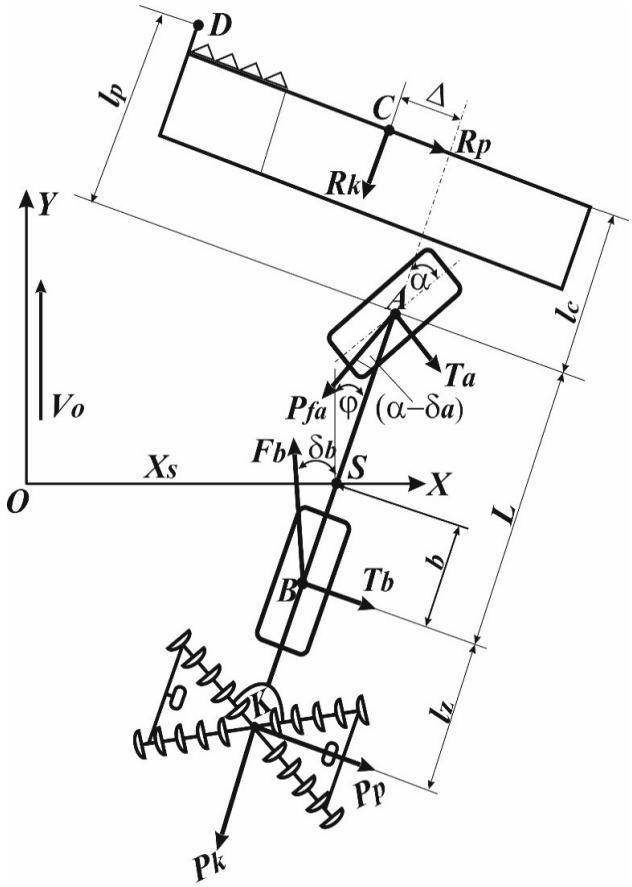


Fig. 2 Harvesting unit diagram with the fixed junction of a tillage machine

The output functioning parameters of the considered dynamic system are:

1. tractor's mass centre transverse displacement X_s;
2. tractor heading angle φ;
3. disc harrow turning angle β.

From equations system (1) under the condition $\beta = \dot{\beta} = \ddot{\beta} = 0$ it is not difficult to obtain the mathematical model of harvesting unit movement in the horizontal plane when the tillage machine is fixedly in conjunction with the tractor (Fig. 2):

$$K_{11} \cdot X_s(p) + K_{12} \cdot \varphi(p) = F_{11} \cdot \alpha(p) + F_{12} \cdot 1(p)$$
$$(K_{21} \cdot X_s(p) + K_{22} \cdot \varphi(p) = F_{21} \cdot \alpha(p) + F_{22} \cdot 1(p) \quad (2)$$

where: $F_{12} = R_p + P_p$; $F_{22} = R_p(l_c + L - b) - R_k \cdot \Delta - P_p \cdot (l_z + b)$

With the use of mathematical models (1) and (2), the necessary transfer functions can be created, and the amplitude (AFC) and phase (PFC) frequency characteristics of dynamic control system processing can be built. The further algorithm of theoretical studies is as follows: the variant of the unit whose AFC and PFC are closest to perfect (ideal) is preferable. When working out the control action, the perfect AFC is 1, and PFC is 0 (Popovich and Kovalchuk, 2007; Nadykto et al., 2022).

Experimental procedure

In the process of calculating the necessary transfer functions, as well as the corresponding AFC and PFC, the following values of the harvesting unit design parameters were used: M_a = 9800–10,500 kg; J_a = 53,550–72,000 kg·m^2; J_m = 3800 kg·m^2; k_a = 115 kN·rad^{-1}; k_b = 80 kN·rad^{-1}; P_{fa} = 5 kN; F_b = 12.6 kN; P_r = 7.5 kN; L = 2.86 m; b = 1.0 m; l_z = 1.1–3.0 m; l_c = 3.75 m; Δ = 0.75 m; B_p = 6 m; V_o = 2.5 m·s^{-1}.

To confirm the results of mathematical modeling in the field, the harvesting unit was studied as part of the HTZ-16131 tractor (Ukraine) with the ZHVN-6B header (Ukraine) and the BDN-3 disc harrow (Fig. 3). The tractor was set up for forward travel. The disc harrow was hung on both with the possibility of rotation in the horizontal plane at an angle of $\beta = \pm 8°$ and fixedly.



Fig. 3 Harvesting unit

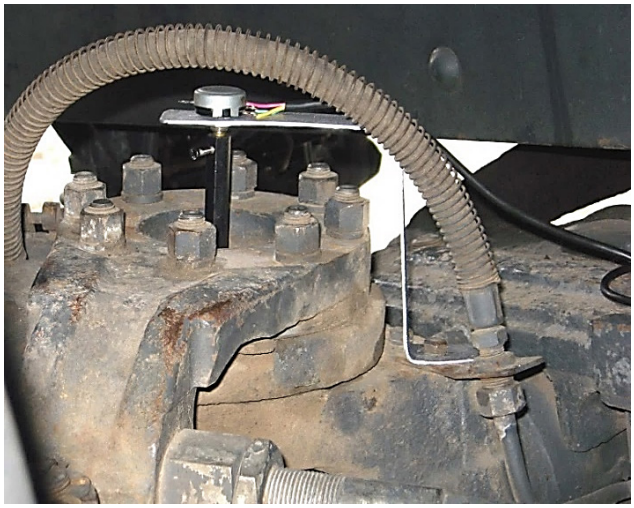


Fig. 4 Variable resistor CP-3A

This harvesting unit operated on harvesting winter wheat. The experimental field was divided into control sites 250 m long each. The first 50 m of each site was used to accelerate the harvesting unit. On the remaining 200 m, it performed functional movement in three repetitions. The formula calculated the velocity of its movement: $V_o = 200 \cdot t^{-1}$ (m·s^{-1}). Here, t is the time for the harvesting unit to pass through the control site. We used an electronic stopwatch KHP PC3860 (China) to register it with a measurement error of 0.01 s.

During the harvesting unit operating movement, using Arduino Uno (Italy), the tractor's heading angle (φ) and its steered wheels' rotation angle (α) were recorded. To measure the parameter φ, a Gy-521 MPU-6050 gyroscope (China) was used. The parameter α was recorded using a variable resistor CP-3A (Ukraine) with a linear characteristic and a nominal value of 470 Ω. The Gy-521 MPU-6050 gyroscope was installed on the tractor's hood at the point of its mass centre longitudinal coordinate. The resistor CP-3A was installed on the axis of the tractor steering wheel's pivot (Fig. 4).



Fig. 5 Kit for measuring tillage depth

The values of the angles α and φ read by Arduino Uno using the SD SPI module (China) were recorded on a CD card. The digitized experimental data were used to calculate the standard deviations and normalized spectral densities of the parameters α and φ oscillations. In addition, we calculated and analyzed the normalized cross-correlation functions of the relationship between fluctuations in the angles α and φ both in the swivel and fixed conjunction of the disc harrow with the tractor in the horizontal plane.

Before experimental studies of the harvesting unit, the characteristics of the winter wheat harvested area were determined. Subjects to measurement were:

1 soil moisture and soil density in the 0–10 cm layer;
2. mean height of wheat plants, cm;
3. wheat yield, tonne·ha^{-1};
4. crops' weed density, g·m^{-2};
5. wheat stubble height, cm;
6. depth of tillage with a disc harrow, cm.

Instruments and the method of their application for measuring soil moisture and soil density are quite substantively described in (Kollárová et al., 2015; Nadykto et al., 2020). The height of winter wheat plants and stubbles was determined along the field diagonal with a ruler 1 m long, with a measurement error of ±0.5 cm. The number of such measurements was 300, and the measurement step was 0.5 m.

The weed density in wheat crops and their yield were determined using a wooden frame with an area of 1 m^2. The distance between 30 measurement zones along the field's diagonal was at least 10 m. The mass of weeds and wheat grains that fell into the frame zone after threshing its spikelets was determined using an Axis AD 200 electronic scales (Poland), the measurement error of which was 0.001 g.

The depth of tillage with a disc harrow was measured along the diagonal of the plot in two repetitions. The measurement step for this parameter was 0.2 m. The number of this parameter measurements in each repetition was 300. To measure the tillage depth, we used a kit (Fig. 5) created by us based on the ultrasonic sensor HC-SR04 (China) and the Arduino UNO device (Italy). The error in measuring the tillage depth by this kit does not exceed 0.5 cm.

Results and discussion

Let's assume that during the harvesting unit movement, the tractor driver tries to combine the sighting point *D* (Fig. 1) with the edge of the harvested crop array. In this case, it is logical to take the transverse displacement of this point as a control action. The tractor responds to this offset by changing the X_s coordinate accordingly. The transfer function $W_{DS}(p)$, built based on the obtained model (2) and reflecting

the transformation nature of the point displacement *D* into the transverse displacement (*S*), has the form:

$$W_{DS}(p)=\frac{D_a+D_\varphi\cdot Y}{D_a+D_\varphi(L-b)} \quad (3)$$

where: D_a – determinant from the model (2) coefficients, which describes the changing process of the tractor's steered wheels' rotation angle (α); *D*φ – coefficient, which describes the changing process of the tractor's heading angle (φ); $Y = SD$ – distance from point *S* to sighting point *D* (Fig. 1). This linear parameter can be determined from the equation:

$$SD=\sqrt{(L-b+l_p)^2+\left(\frac{B_p}{2}+\Delta\right)^2} \quad (4)$$

where: B_p – header operating width, m

In expanded form, the transfer function (3) has the following format:

$$W_a(p)=\frac{F_2\cdot p^2+F_1\cdot p+F_o}{C_2\cdot p^2+C_1\cdot p+C_o} \quad (5)$$

where:
$F_2 = f_{11} \cdot A_{21} + f_{21} \cdot A_{11} \cdot SD$
$F_1 = f_{11} \cdot A_{22} - f_{21} \cdot A_{13} + (f_{21} \cdot A_{12} - f_{11} \cdot A_{24}) \cdot SD$
$C_2 = f_{11} \cdot A_{21} + f_{21} \cdot A_{11}(L - b)$
$C_1 = f_{11} \cdot A_{22} - f_{21} \cdot A_{13} + (f_{21} \cdot A_{12} - f_{11} \cdot A_{24}) \cdot (L - b)$
$F_o = C_o = f_{11} \cdot A_{23} - f_{21} \cdot A_{14}$

The analysis of function (5) shows that to avoid overshooting the input action by the dynamic system under consideration, the exponent of its numerator should be reduced by at least one. Let's consider two possible solutions to this issue. According to the first of them, the coefficient F_o must be equal to 0. In this case, Eq. (5) takes the form:

$$W_a(p)=\frac{F_2\cdot p+F_1}{F_2\cdot p^2+C_1\cdot p+C_o} \quad (6)$$

As indicated in Eq. (5):

$$F_o = C_o = f_{11} \cdot A_{23} - f_{21} \cdot A_{14}$$

It follows that F_o will be equal to 0, provided that:

$$f_{11} \cdot A_{23} = f_{21} \cdot A_{14} \quad (7)$$

If we substitute the values of the coefficients used from Eq. (1) into Eq. (7), then we obtain:

$$-k_a\left[(k_a + P_{fa})\,(L - b) + (F_b - k_b)b\right] = (L - b)\,k_a\,(F_b - k_a - k_b - P_{fa}) \quad (8)$$

The analysis of Eq. (8) shows that, theoretically, it is valid only if $F_b = k_b$. However, in practice, this is almost impossible to achieve. For almost any tractor, the resistance coefficient to the yaw of its tires k_b is almost ten times greater than the force F_b value.

Following the second option, the transfer function (5) should have $F_2 = 0$. In this case, it takes the following form:

$$W_a(p)=\frac{F_1\cdot p+F_o}{C_2\cdot p^2+C_1\cdot p+C_o} \quad (9)$$

As follows from Eq. (5):

$$F_2 = f_{11} \cdot A_{21} + f_{21} \cdot A_{11} \cdot SD \quad (10)$$

If we substitute the values of all coefficients from Eq. (1) and Eq. (4) into Eq. (10) and then carry out the appropriate transformations, it turns out that the condition $F_2 = 0$ will be satisfied when:

$$l_p=-(L-b)+\sqrt{\left(\frac{J_a}{(L-b)\cdot M_a}\right)^2-\left(\frac{B_p}{2}+\Delta\right)^2} \quad (11)$$

Let's analyze the resulting equation. The parameter l_p is the extension of the sighting point forward (point *D*, Fig. 1). During the movement of the harvesting unit, the tractor driver controls the tractor so that the distance from the sighting point to the edge of the harvested array is as tiny as possible. Ideally, this distance should be zero. Further, for all harvesting units, there is a minimum value of the $l_p(l_{pmin})$ parameter. Under the conditions of mathematical modeling, it can only be increased. It follows that:

$$l_p=\sqrt{\left(\frac{J_s}{(L-b)\cdot M_a}\right)^2-\left(\frac{B_p}{2}+\Delta\right)^2}\geq l_{pmin}+(L-b) \quad (12)$$

The equality of the sighting point actual offset value to the minimum one (that is, $l_p = l_{pmin}$) is possible if the condition is met:

$$b = L \quad (13)$$

The tractor's mass centre must be placed above its front axle to achieve it. In practice, such a constructive solution is somewhat problematic to implement. At the same time, the tractor with a displaced centre of mass in the direction of the front axle (integrated circuit), due to the larger value of the parameter *b*, meets Eq. (13) more than the classical circuit tractor.

Further, for the root value of Eq. (12) to be greater than zero, the following condition must be satisfied:

$$\frac{J_a}{(L-b)\cdot M_a}>\frac{B_p}{2}+\Delta \quad (14)$$

The analysis of Eq. (14) shows that the most realistic way of its implementation is to increase the moment of inertia J_a. In practice, this can be achieved by a fixed junction of the used disc tillage machine to the tractor. In the harvesting unit, we are considering that the value of the parameter J_a increases by 44% in this case.

Mathematical modeling has established that, as a result, the fixed junction of the tillage machine to the tractor causes a better transformation of the input action by the harvesting unit. Thus, in the frequency range of the tractor's steered wheels rotation angle oscillations $\omega = 0–2\ s^{-1}$, the calculated

AFC of this unit practically corresponds to the perfect one (curve 2, Fig. 6). The harvesting unit with a tillage machine swivelly attached to the tractor works out the same input action with under-regulation that is undesirable for practice (curve 1, Fig. 6).

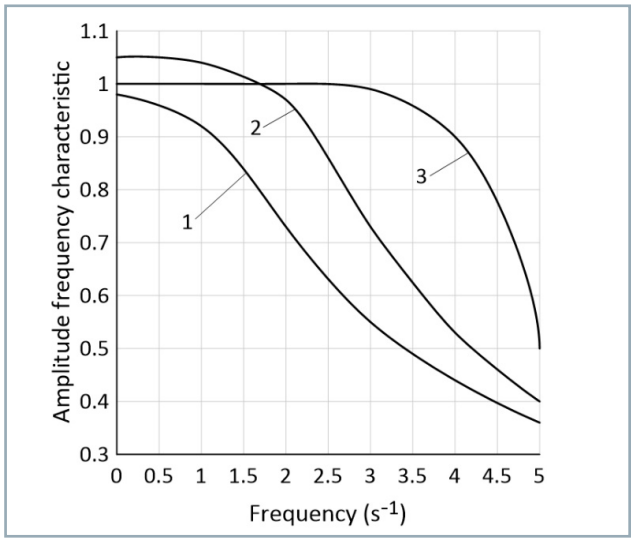


Fig. 6 AFC with swivel (1) and fixed (2) junction disc harrow to the tractor (3 – perfect AFC)

It is pretty clear that a harvesting unit with a large moment of inertia tends to respond more slowly to the control input. In the variant with a fixed junction of the disc harrow, the delay in changing the heading angle of the tractor by changing the angle α (and hence by changing the transverse displacement of its steered wheels) is greater (curve 2, Fig. 7). At the same time, this difference is more or less significant at a frequency ω exceeding 1 s^{-1}. But, as practice shows, such a mode of harvesting unit movement is unlikely. Therefore, to ensure acceptable controllability of the harvesting unit movement, it is advisable to junction the disc harrow fixedly to the tractor in a horizontal plane.

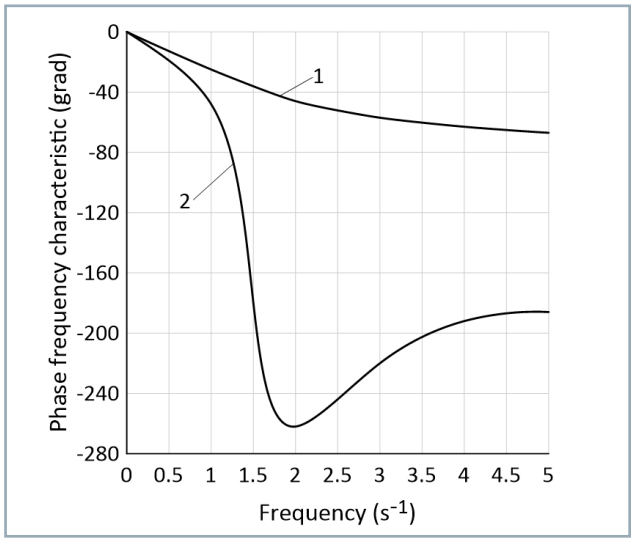


Fig. 7 PFC with swivel (1) and fixed (2) junction disc harrow to the tractor (3 – perfect AFC)

The results of experimental studies also support this decision. The conditions for their implementation are presented in Table 1.

Table 1 Characteristics of the winter wheat experimental site

Index	Value
Soil moisture in the layer 0–10 cm (%)	15.4
Soil bulk density in the layer 0–10 cm (g·m^{-3})	1.24
Winter wheat yield (tt·ha^{-1})	4.50
Mean plant height (m)	0.72
Weeds density (g·m^{-2})	14.5
Wheat stubble height (cm)	14.3
Stubble disc depth (cm)	8.9

According to the data obtained, when the disc harrow is swivel conjunction with the tractor, the oscillations spectrum of its heading angle at the unit speed of 2.56 m·s^{-1} is concentrated in the frequency range of 0–3.5 s^{-1} (curve 1, Fig. 8). In the case of their fixed conjunction and movement speed of 2.58 m·s^{-1}, the spectrum of the parameter φ oscillations becomes narrower, concentrating in the frequency range of 0–2.0 s^{-1} (curve 1, Fig. 8).

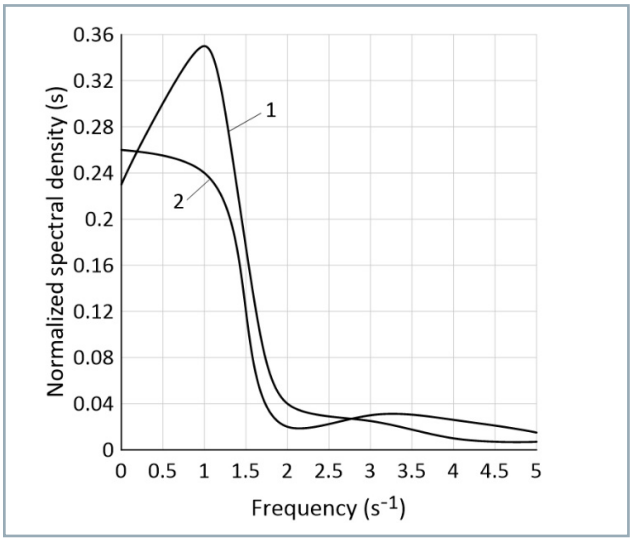


Fig. 8 Normalized spectral oscillation densities of the tractor heading angle with swivel (1) and fixed (2) junction of the tillage machine

Consider the results of the variance analysis. When the disc harrow and the tractor were in swivel conjunction, the variance of heading angle oscillations of the latter was 3.24 grad^2. With a fixed option of their conjunction, the value of this estimated parameter decreased to 2.15 grad^2. The actual value of the *F*-test is 1.5. At a statistical significance level of 0.05, this is less than the tabular value of this criterion, equal to 1.39. Ultimately, it can be stated that the zero hypothesis about the equality of tractor's heading angle oscillations variances with swivel (option 1) and fixed (option 2) conjunctions of the disc harrow is rejected. That is, in the second diagram version of the harvesting unit, the

variance of tractor's angular oscillations in the horizontal plane is significantly and not by chance smaller.

The specified reduction in variance is provided by a closer relationship between the tractor's steered wheels' angle rotation (α) and heading angle (φ). The nature of this relationship is revealed by the normalized cross correlation function between the parameters α and φ. The maximum positive value of this function is 0.82 for harvesting unit option 2 (curve 2, Fig. 9). At the same time, for unit option 1, the maximum value of this function (curve 1, Fig. 9) reaches only 0.60, that is, almost 27% less.

Let's note one more interesting fact. The maxima of the considered normalized cross-correlation functions are in the first quadrant. And this means that the actual input action in the considered dynamic system is the tractor's steered wheels' rotation angle (α), and the output parameter is its heading angle (φ). On the other hand, if the maximum values of these functions were in the second quadrant, then the angle φ would consider as the input action, and the reaction of the tractor in the form of turning its steered wheels by the angle α would consider as the output action.

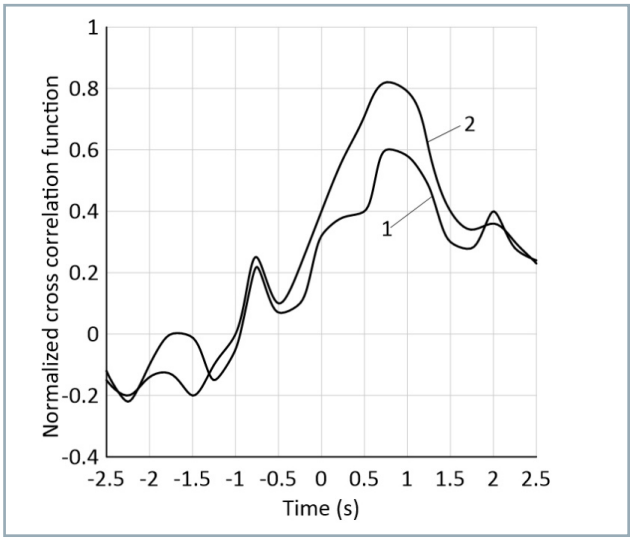


Fig. 9 Normalized cross correlation functions of angle oscillations α and φ with swivel (1) and fixed (2) disc harrow conjunctions to the tractor

The horizontal distance from the maximum value of the normalized cross correlation function to the vertical zero axis characterizes the phase shift, that is, the delay time of the response of the output parameter to a change in the input. In this case, for both functions, this time is almost the same and is approximately 0.75 s. This fact is comparable with the result described above in the analysis of Fig. 7.

Conclusion

The mathematical model of plane-parallel movement in the horizontal plane of a harvesting unit as part of a tractor with a front-mounted header and a rear-mounted tillage machine (disc harrow) has been developed. Based on the analysis of the obtained equations systems, such dynamic system movement controllability has been estimated in the reaction form of its mass centre transverse displacement to the transverse displacement of the sight point with swivel (option 1) and fixed (option 2) conjunction of a tillage machine to the tractor.

As a result of mathematical modeling, it was found that harvesting unit option 2 has better motion controllability than unit option 1. The amplitude frequency characteristic of such a unit when it works out the control action in the frequency range 0–2 s^{-1} is quite close to perfect. In addition to everything, according to option 2, the unit has a higher (by 37%) correlation between tractor's steered wheels' rotation angle oscillations and the oscillations of its heading angle. As a result, the oscillations variance of the latter is significantly and naturally less than in the harvesting unit with the swivel conjunction of the tillage tool (disk harrow).

The results obtained should be considered when choosing a unit design diagram for harvesting agricultural crops simultaneously with chopping their stubble.

Acknowledgement

This article was supported by the projects VEGA 1/0102/21: Reducing Chemical Loads and Degradation of Agricultural and Forestry Soils by Selecting Appropriate Agri-Technology with Regard to Climate Change and KEGA 016SPU-4/2021: Implementation of Modern Educational Approaches and Tools to Enhance Creativity and Practical Skills of Graduates with Special Focus on Agricultural and Forestry Science Using.

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