INFLUENCE OF MACHINE-TRACTOR SET CONSTRUCTIONAL PARAMETERS ON KINEMATIC DISCREPANCY IN TRACTOR WHEELS

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Abstract
The article discusses methods of influencing a kinematic discrepancy K_v in a tractor with identical wheels as a part of the trailed unit. A net traction of the trailed unit in this case is represented by vertical and horizontal components. While draft resistance must be increased, fulfillment of the condition $K_v = 1$ requires relevant increasing of the air pressure in tractor's wheels. In real using conditions the tractor has to be equipped with a device for automatic changing tires air pressure of the wheels depending of the trailed machine draft resistance. The greater the horizontal component value of the trailed unit net traction, the greater horizontal coordinate application of this component must be shifted to the left relatively to the vertical axle which passes through the rotation center tractor's rear wheels. Ideally, the tractor should have a pendulous mechanism which will keep the value of the kinematic discrepancy K_v close to 1.

Key words: *air pressure; slippage; kinematic discrepancy.*

INTRODUCTION

One of the main trends in the development of modern tractor construction is the four-wheel drive tractors production. The drives of their front and rear axles have a blocked mechanical joint. These axles have the same speed of step forward motion, while the circumferential velocities of the front and rear wheels are usually not equal even if they are of the same size. As a result, due to the difference in the slippage of front (δ_r) and rear (δ_r) tractor wheels a kinematic discrepancy arises, being estimated by the coefficient K_v (*Gurevicius et al., 2016*).

Analysis of the published articles shows that the researchers mostly emphasized the effect of the coefficient K_v value on the performance of the tractor with different agricultural machines (including trailed). But at the same time, they usually a) considered only horizontal component of the machine draft resistance; b) do not researched the effect of the joining coordinates of the agricultural machine with tractor on realization of the condition $K_v = 1$.

In the paper (*Gurevicius et al.*, 2016) it has been proved that increasing $K_v > 1$ leads to an increase tractor's rolling resistance in all investigated field conditions.

In order to provide, for example, the condition $K_v = 1$ for Case IH Farmall U Pro 115 tractor you should set the air pressure in the front tires of its wheels at 0.7 bar and in the rear tires – 2.3 bar.

The cases, when increasing tractor's rolling resistance under kinematic discrepancy in the drive of its wheels take place, have been given in the papers (*Hegazy and Sandu, 2013*) and *(Damanauskas and Janulevičius, 2015*).

Reducing traction effort and increasing fuel consumption with an increased value of the K_v coefficient have been determined by researchers in the studies (*Senetore and Sandu, 2011*) and *(Molari et al., 2012*).

The authors Vantsevich and Asme (Vantsevich and Asme, 2014) tried to determine the influence of the kinematic difference in the drive of the tractor wheels not only on its traction characteristics, but also on the stability of movement in the horizontal plane.

As the researchers prove (*Stoilov and Kostadinov, 2009*), the difference in the coefficient $K_v > 1$ is due to the difference in the rolling radii tractor's front and rear wheels. This difference is caused by fluctuations in the vertical load on tractor's axles. Influence changing of the mentioned load on the value of coefficient K_v has been considered in the paper (*Janulevičius et al., 2013*).

At the same time, the load has been considered by the authors is formed by external forces, having only

vertical direction. Under actually operating conditions of the tractor the external load acting on it has either a horizontal direction or it is inclined to the horizon at some angle (*Bulgakov et al., 2016*).
In this connection, the aim of this work was impact study of the joining coordinates of the agricultural machine with tractor, represented by the horizontal and vertical components of its draft resistance, on the kinematic discrepancy coefficient and to do an experimental review of theoretical research.

MATERIALS AND METHODS

In the paper *(Gurevicius et al., 2016)* it was proposed to determine the kinematic difference coefficient by the following dependence:

$$K_v = (1-\delta_r)\cdot(1-\delta_f)^{-1}$$

Very often a different formula is used to calculate this coefficient *(Guskov, 2008)*:

$$K_v = (R_r - \omega_r)\cdot(R_f - \omega_f)^{-1} \qquad (2)$$

where R_r, R_f, and ω_r, ω_f – rolling radius and rotation frequencies of rear and front tractor wheels respectively.
For a tractor with identical front and rear wheels the equation for defining the kinematic discrepancy coefficient ($K_v = 1$) may be calculated from the following equation:

$$K_v = \rho_b\left(2\pi\cdot\rho_a\cdot\sqrt{R_k^3\cdot r_0} - N_a\right)\cdot\left[\rho_a\left(2\pi\cdot\rho_b\sqrt{R_k^3}\cdot r_0 - N_b\right)\right]^{-1} \qquad (3)$$

where ρ_a, ρ_b – tires air pressure of the front and rear tractor's wheels respectively, MPa; R_k, r_0 – the outer radius and cross-section radius tractor's wheel tire, m; N_a, N_b – the vertical load applied to the front and rear tractor's axles respectively, *N*.
For the case, when $K_v = 1$ the equation (3) with enough accuracy for practice takes the following form:

$$\rho_b\cdot(\rho_a)^{-1} = N_b\cdot(N_a)^{-1} \qquad (4)$$

As we can see, at the lack of kinematic discrepancy in drive of the tractor running gear with identical wheels, the ratio of the air pressure in their tires is directly proportional to the ratio of the vertical loads on the axles. This leads to significant conclusion. Namely, having got the values of N_a and N_b in advance, it is possible to choose such values of the air pressure in the tractor tires ρ_a and ρ_b that will provide exact fulfillment of the condition (4).
It should be noted that a similar task has been already decided by *(Janulevicius et al., 2014)*. However, the forces they had examined on the tractor were mainly of the vertical direction.

As a practical example of the problem being solved by us, let us consider the procedure for determining N_a and N_b parameters for the trailed version of the machine-tractor set (MTS).
Let us agree, that the trailed MTS in the longitudinal-vertical plane is being affected by horizontal (R_x) and vertical ($R_x\cdot\tan\beta_z$) draft resistance components of the agricultural machine (Fig. 1).

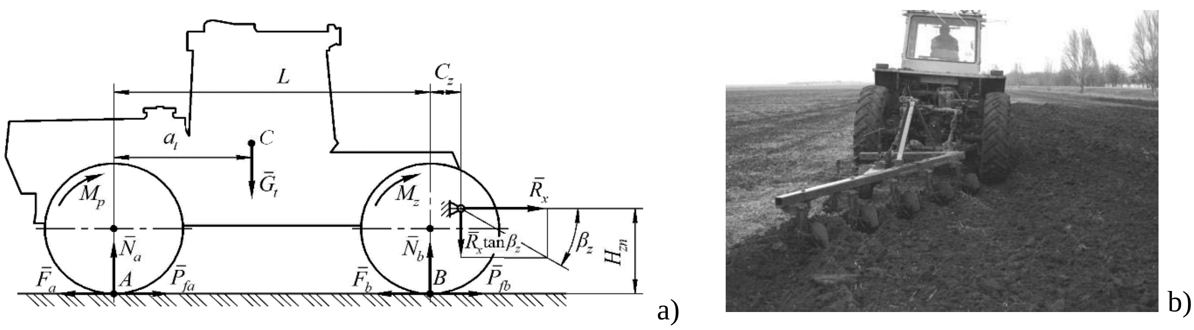

Fig. 1 Trailed version of the machine-tractor set (MTS):
a) The scheme of forces acting on the tractor in the longitudinal-vertical plane;
b) Tractor HTZ-160 with five-bottom plow PLN-5-35

Brief technical description of the tractor HTZ-160: Total mass (kg) – 8400; Mass on front wheels (kg) – 5000; Mass on rear wheels (kg) – 3400; Wheel base (L, mm) – 2860; Tires – 16,9R38; Coordinate a_t (Fig. 1a, m) – 1.16.

Together with the tractor's weight G_t the gross tractions F_a and F_b, the rolling resistances P_{fa} and P_{fb}, as well as the rolling resistance moments M_p and M_z form some distribution of the surface vertical reaction forces N_a and N_b.
To determine the reactions N_a and N_b, as it is well known, it is sufficient use two equations of forces and moments equilibrium acting at MTS under consideration. In this case, such equations can be the sum of the all vertical forces as well as the sum of the moments acting, for example, with respect to point A (see Fig. 1):

$$\begin{aligned} &N_a + N_b - G_t - R_x \cdot \tan\beta_z = 0 \\ &G_t \cdot a_t - N_b \cdot L + R_x \cdot \tan\beta_z \cdot (C_z + L) + R_x \cdot H_{zn} = 0 \end{aligned} \tag{5}$$

The essence of the constructional parameters β_z, a_t, L, C_z and H_{zn} have been included in the equation (5), is quite clear from Fig. 1.
The solution of the equations system (5) leads to the following result:

$$\begin{aligned} &N_a = \left[G_t \cdot (L - a_t) - R_x \cdot (\tan\beta \cdot C_z + H_{zn})\right] \cdot L^{-1} \\ &N_b = \left[G_t \cdot a_t + R_x \cdot (\tan\beta_z \cdot (C_z + L) + H_{zn})\right] \cdot L^{-1} \end{aligned} \tag{6}$$

Taking into account the formula system (5), the equation (3) takes the form:

$$\rho_b \cdot (\rho_a)^{-1} = \left(G_t \cdot a_t + R_x\left[\tan\beta_z \cdot (C_z + L) + H_{zn}\right]\right) \cdot \left[G_t(L - a_t) - R_x(\tan\beta_z \cdot C_z + H_{zn})\right]^{-1} \tag{7}$$

The equation (7) as well as formula (2) was used for subsequent calculations.
This formula is absolutely new. It is this one that allows to select such coordinate values of the machine's connection to the tractor, which allow to fulfill the condition $K_v = 1$. At the same time, here both horizontal (R_x) and vertical ($R_x \cdot \tan\beta_z$) components of the agricultural machine draft resistance are taken into account.
The HTZ-160 tractor with the same front and rear wheels (Fig. 2) was taken as the physical object of research. It was used with the five-bottom plow PLN-5-35 (Fig. 1b). Its working width (B_p) is equal 1.75 m.

Fig. 2 Tractor HTZ-160 with the same front and rear wheels

Fig. 3 Tractor's wheel with sensor-hermetic contact

The reliability of equation (7) was determined by the following method. Three options for installing air pressure in the tractor's tires were adopted. In the tires of front axle air pressure was constant and equal $\rho_a = 0.100$ MPa. In the rear axle tires it had three different values: $\rho_b = 0.100$, 0.108 and 0.115 MPa.

From equation (7) for each option of the pressure installation in the tractor's tires the plow's draft resistance horizontal component R_x was determined. The calculations were carried out with the following values of the parameters incoming into the equation (7): $G_t = 82.4$ kN; $a_t = 1.16$ m; $L = 2.86$ m. $C_z = 0.58$ m; $H_{zn} = 0.6$ m; $\beta_z = 8^o$.
Parameter β_z – it is inclination angle of the lower links of the tractor's three-point hitch linkage during its work with plow. The value of this parameter was determined by protractor while plowing set was stopped.

Tractor's weight G_t was determined by weighting it with a dynamometer DPU-5. The measurement accuracy was equal 0.5 kN.
Plow draft resistance (R_x) and plowing depth (h) are connected by such well-known equation:

$$R_x = K_o \cdot h \cdot B_p , \qquad (8)$$

where K_o – specific plow's draft resistance. According to our research the mean of this parameter in the soil conditions of south Ukraine, for example, is equal 65 kN·m^{-2}.
For each values of force R_x the plowing width from formula (8) was determined. In field conditions the plow was adjusted to three tillage depths (22, 26 and 28 cm). The experiments were performed on soil with a moisture content of 15.4% and a density of 1.28 g·cm^{-3}.

In each adjusting option the plowing set moved on the test section of 200 m each. The replication of each experiment was threefold. After each pass of the plowing set the real plowing depth and value of the cinematic discrepancy K_v were measured.
For the tractor with identical wheels equation (2) taking into account equation (4) looks like this:

$$K_v = \omega_r \cdot \left(\omega_f\right)^{-1} \qquad (9)$$

For measuring wheels rotation frequencies (ω_r, ω_f) we used sensor-hermetic contacts (Fig. 3). The electrical signal from them was given by analog-to-digital converter and were transferred to a computer, where the main statistical characteristics were determined.
The real values of the coefficient K_v, calculated using the formula (9), were compared with 1. After this the decision was made on the adequacy of the equation (7).
In the end, using equation (7), we established the laws of such a choice of parameters ρ_a, ρ_b, C_z and H_{zn} that would ensure the fulfillment of the condition $K_v = 1$.
The following statistical characteristics were calculated for the data obtained during the experimental studies: average value; mean square deviation σ and the coefficient of variation ν.

RESULTS AND DISCUSSION

Analysis of the experimental data shown that plowing depth real values were in such confidence intervals: a) for the first plow adjustment option – 22.3±1.2 cm; b) for second one – 26.4±2.1 cm; c) for third one – 29.8±1.3 cm. All variation coefficient do not exceed 8%.

Tab. 1 Results of determining the actual depth of ploughing

Indicator	Processing results		
	Plot 1	Plot 2	Plot 3
Specified depth, cm	22	26	28
Average value, cm	22.3	26.4	29.8
Average square deviation σ, cm	1.2	2.1	1.3
Coefficient of variation ν, %	5.38	7.95	4.36

As a result, for all options of plowing depth the calculated values of the coefficient K_v is very close to 1 (Fig. 4). The maximum difference of the compared data does not exceed 1.4%.

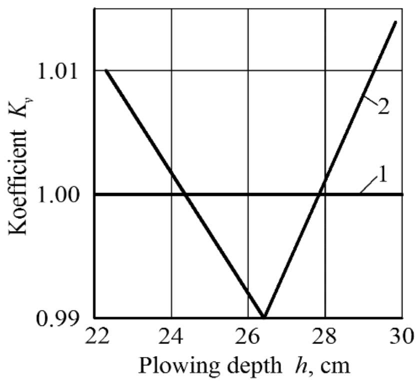

Fig. 4 Deviation of the coefficient K_v values (2) from K_v = 1 (1) at different plowing depth

This, as statement in article (Damanauskas, 2018), is almost perfect result. In this study it allows us to consider the equation (7) adequate and therefore suitable for use in further analysis.
Ensuring of the condition $K_v = 1$ while the draft traction is acting ($R_x \neq 0$) may be reached by means of corresponding air pressure increase in the tractor's rear tires (ρ_b) or decrease in front ones (ρ_a) (Fig. 5).

Let us try to analyze the dependence presented in Fig. 5. The average value of the trailed agricultural machine draft resistance, for example, is $R_x = 36$ kN. As practice shows, such value of the tractor HTZ-160 net traction is typical when it using with a majority of a tillage machines. Furthermore, an oscillation variation coefficient of the force R_x is an average of 10%. This means that the draft resistance of the trailed machine will vary within the range from 32 to 40 kN. But in this case, as it follows from Fig. 5, the air pressure in the rear tires of the tractor should vary from 0.128 to 0.148 MPa. In the tractor's front tires the air pressure should decrease from 0.112 to 0.098 MPa.

The horizontal (R_x) and vertical ($R_x \cdot \tan \beta_z$) components of the trailer traction resistance are applied to the tractor at the point with C_z and H_{zn} coordinates (Fig. 1).

As calculations of the formulae system (7) show, the dependence of the H_{zn} parameter from the value of draft resistance (R_x) is insignificant (Fig. 6). Namely, with an increasing R_x force from 30 to 40 kN and providing the condition $K_v = 1$, H_{zn} value decreases at 16 cm only (Fig. 6).

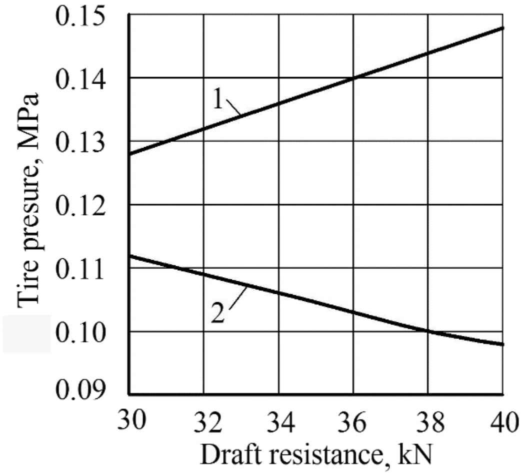

Fig. 5 Influence draft resistance of trailed agricultural machine on air pressure in tractor's rear (1) and front (2) tires

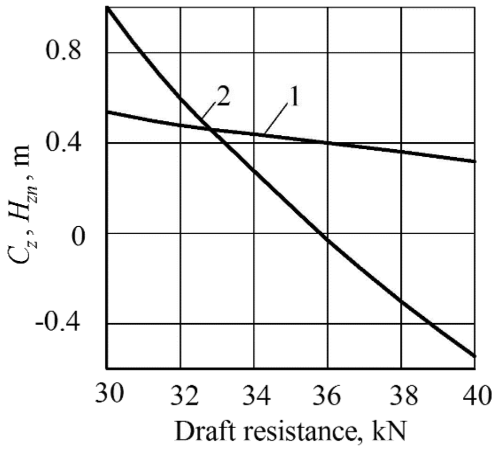

Fig. 6 Influence draft resistance of trailed agricultural machine (R_x) on H_{zn} (1) and C_z (2) parameters

But we have absolutely different situation with the parameter C_z. By means of calculations of the formulae system (6) it has been found that if $R_x = 30$ kN, then the value of C_z is equal 1 m (Fig. 6).
As the value of the force R_x increases, the horizontal coordinate of the application of the trailer traction resistance must be shifted to the left of the vertical axis passing through the rotation center of the tractor rear wheels. For the case of $R_x = 40$ kN this displacement should be 0.55 m ($C_z = -0.55$ m, Fig. 6).
This result may testify that the tractor should have a mechanism for automatic longitudinal displacement of the trailer attachment point to it. The value of this displacement depends from the draft resistance of the agricultural machine.
In practice such the constructional decision can be carried out by means of the well-known pendulous mechanism. As a result, it enables to keep the kinematic discrepancy K_v value in a value close to 1.

CONCLUSIONS

1. The mathematical model, allowing to define the coefficient of kinematic discrepancy of K_v of wheeled all-wheel drive tractor axles by changing some construction parameters is developed.
2. Experimental studies have confirmed the adequacy of the presented mathematical model. At application of the recommended constructional parameters the coefficient of kinematic discrepancy K_v is close to one.

3. To ensure the condition $K_v = 1$ increasing of the trailed machine draft resistance requires a corresponding change of the air pressure in tractor's front and rear tires. Namely, the bigger trailed machine's draft resistance, the bigger air pressure in tractor's rear tires and lower in the front ones.
4. Under the real conditions of the tractor operation it should be equipped with a device that automatically changes the air pressure in the tires of its wheels depending on the value of the trailed machine draft resistance.

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