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TRACTION PROPERTIES OF SUSPENSION SYSTEMS OF FARM TRACTORS

Summary

Presently, great attention is paid to development of new types of suspension systems of farm tractors and mobile machines which have a decreased unit pressure on soil. Their traction properties must be taken into consideration when values of suspension systems parameters are determined. The coefficient of operation performance was assumed as a criterion defining this property. The article presents an analysis of component relations of the coefficient of operation performance with the suspension system parameters. Relations between resistance and soil deformation, used by many authors were applied for calculation of the rolling resistance. It was proved that the rolling resistance of the driving source decreases when the number of support wheels increases. In order to reduce deformation of soil under the towing power it is recommended to use a tyre tread, which ensures sufficient adhesion to soil, not as a result of shearing soil with a tread, but as a result of tread friction on soil.

Key words*: system, traction, tractor, resistance, rolling*

WŁAŚCIWOŚCI TRAKCYJNE UKŁADÓW JEZDNYCH CIĄGNIKÓW ROLNICZYCH

Streszczenie

Obecnie dużo uwagi poświęca się opracowaniu nowych typów układów jezdnych ciągników rolniczych oraz maszyn samojezdnych charakteryzujących się obniżonym naciskiem jednostkowym na glebę. Przy ustalaniu wartości parametrów układów jezdnych konieczne jest uwzględnienie ich właściwości trakcyjnych. Jako kryterium, charakteryzujące tę właściwość przyjęto współczynnik efektywności działania. W artykule zamieszczono analizę zależności składowych współczynnika efektywności działania od parametrów układu jezdnego. Przy obliczeniach siły oporu przetaczania wykorzystano stosowane przez wielu autorów zależności między oporem a deformacją gleby. Wykazano, że opory przetaczania źródła napędu zmniejszają się przy zwiększaniu liczby kół podporowych. W celu obniżenia deformacji gleby podczas działania siły uciągu zaleca się stosowanie bieżnika ogumienia, zapewniającego dostateczne sczepienie z glebą nie w efekcie ścinania gleby bieżnikiem, a w efekcie tarcia bieżnika o glebę.

Słowa kluczowe*: układ, trakcja, ciągnik, opór, przetaczanie*

1. Introduction

In multi-suspension systems traction properties manifest in various ways in relation to the structure of a suspension system [11, 14]. In tractors and machines which are connected, suspension systems with the structure of wheels which move one after another in the same track are the most popular [2, 4, 6, 12].

The coefficient of operation performance is a basic criterion which defines mobile machine modernity. The value of this coefficient is defined with the following relation:

$$\eta = \eta_{mp} \cdot \eta_f \cdot \eta_\delta ,$$

where: η_{mp} – coefficient which includes mechanical resistance of the driving gear; η_f - coefficient which includes rolling resistance; η_δ – coefficient which includes driving wheels slips.

Elements of COP η_f and η_δ include energy losses related to vertical and horizontal soil deformation which increases along with the decrease of those elements. Values η_f and η_δ define the coefficient of operation performance of the suspension system as follows:

$$\eta_{xc} = \eta_f \cdot \eta_\delta = \left(1 - \frac{P_f}{P_k}\right)(1-\delta),$$

where: P_f – rolling resistance of the wheel system, N;

P_k – horizontal towing power of the suspension system, N;

δ – driving wheels slip.

Thus, the COP is affected by the rolling resistance, horizontal towing power and wheel slips. We will discuss their changes in relation to the number of axles of the suspension system.

2. Theoretical discussion

We assume that during the movement of the suspension system on soil, rolling resistance depends mainly on the energy losses related to soil deformation A_σ. Work of the vertical soil deformation at the i-crossing of a wheel is:

$$A_{\sigma i} = S \int_{H_{i-1}}^{H_i} \sigma_i(h)dh\,. \qquad (1)$$

The total value of operation after the n-loading is:

$$A_{\sigma n} = S\sum_{i=1}^{n}\int_{H_{i-1}}^{H_i}\sigma_i(h)dh. \qquad (2)$$

The value of work at the i-crossing of a wheel per one rotation and after n-crossings will be:

$$A_{\sigma i} = 2\pi\cdot r\cdot B\int_{H_{i-1}}^{H_i}\sigma_i(h)dh, \qquad (3)$$

$$A_{\sigma n} = 2\pi\cdot r\cdot B\sum_{i=1}^{n}\int_{H_{i-1}}^{H_i}\sigma_i(h)dh. \qquad (4)$$

On the other hand, the rolling resistance during one rotation of a wheel is:

$$A = 2\pi\cdot r\cdot P_f. \qquad (5)$$

When comparing right sides of equations (3) and (5) we find the value of the rolling resistance during the i-crossing of a wheel:

$$P_{fi} = B\int_{H_{i-1}}^{H_i}\sigma_i(h)dh. \qquad (6)$$

By analogy, from equations (4) and (5) we find the total rolling resistance of the n-axle suspension system:

$$P_{fn} = B\sum_{i=1}^{n}\int_{H_{i-1}}^{H_i}\sigma_i(h)dh. \qquad (7)$$

We find the total rolling resistance of the n-axle suspension system on strongly scarified soils from the assumption that the function *σ(h)* for these soils is a constant [1]. Therefore, the property of additivity of integration may be attributed to this equation (7),

$$P_{fn} = B\int_0^H\sigma(h)dh.$$

But, the relation of the resistance and bending of a is subject to the relation of the hyperbolic hyperbolic tangent described by V. V. Kacygin [7]:

$$\sigma = p_0 th\frac{k}{p_0}h,$$

where: p_0 – soil bearing capacity, Па; k – coefficient of volumetric soil deformation, N·m^{-3}.

Then, the relation between the rolling resistance and the number of axles of the multi-axle suspension system assumes the following form:

$$P_{fn} = B\frac{p_0^2}{k}\ln\left(\frac{n^{bk/p_0}}{\sqrt{1-q^2/p_0^2}}\right), \qquad (8)$$

where: b – coefficient determined by experiment; q – wheel pressure on soil.

For low-resistance soils, the rolling resistance relation to the number of axles takes the following form:

$$P_{fn} = B\frac{p_0^2}{k}\ln\left(\frac{1}{\sqrt{1-q^2/p_0^2}}\right)(1+k_u\lg n), \qquad (9)$$

where: k_u – coefficient of merging of subsequent deformations.

When analysing the relations (8) and (9) we see that the rolling resistance of each subsequent wheel, situated along the side of the tractor is lower than of the previous one. The horizontal towing power increases after the increase in the number of the suspension system axles [8]. As a result, the coefficient of operation performance of the suspension system and towing also increases. During the mutual impact of the driving wheel and soil, resisting force of soil against shearing, friction forces between the resistance surface of the tyre and soil and shearing force of soil chunks with side ridges of a tread, occur.

Transmission of the rotation moment of wheels is related to slip (towing) δ. At the same time soil deformation and shearing in the horizontal plane takes place. The highest relocation of soil $S_{\max}$ is:

$$S_{\max} = \delta L,$$

where: L - length of the resisting surface of a wheel.

The horizontal towing power developed with the i-axle of the multi-axle suspension system fights the soil shearing forces and friction forces of a tread on soil [8].

$$P_{K\,i} = P_{SD\,i} + P_{TP\,i}. \qquad (10)$$

A horizontal element of the towing power resulting from the shearing resistance of soil is:

$$P_{SD} = (1-k_H)\int_0^{L_i}\nu\,B\,\tau(x)dx, \qquad (11)$$

where: k_H - coefficient of filling the shape of the tyre tread;

L_i - the length of the contact of the i-wheel with soil, m;

ν - coefficient, depending on the soil condition and air pressure in a tyre;

$\tau(x)$ - the function relation between the shearing stress and soil deformation.

V.V. Kacygin et al. [8] suggested the following relation between the shearing stresses and soil deformation:

$$\tau = f_{ck}\sigma\left[1+\frac{f_{np}}{ch(S/k_\partial)}\right]th\left(\frac{S}{k_\partial}\right), \qquad (12)$$

where: f_{ck} - kinematic friction coefficient;

f_{np} - checked (replaceable) friction coefficient,

$$f_{np} = \frac{4f_n - 3f_{ck}}{2f_{ck}},$$

f_n - static friction coefficient;

k_∂ - deformation coefficient, m;

$$k_\partial = S_0\Big/Arch\left(\left(1+\sqrt{1+8f_{np}^{\,2}}\right)\Big/\left(2f_{np}\right)\right),$$

S_0 – deformation size, corresponding to the maximum shearing stress m,

From the relation (11) and (12) we find:

$$P_{SD\,i} = (1-k_H)\int_0^{L_i}\nu\,B\,f_{\text{ск}\,i}\,\sigma_i\left[1+\frac{f_{np\,i}}{ch(\delta\,x/k_\partial)}\right]th\left(\frac{\delta\,x}{k_\partial}\right)dx, \qquad (13)$$

where: dx - the length of the elementary surface.

The contact stress is placed longitudinally on the contact surface of a wheel irregularly. At the approximation of the distribution of stresses with a parabola, the following parabola between the maximum and average stresses was obtained:

$$\sigma_{\max i} = \frac{3}{2}\sigma_{cp\,i} = \frac{3}{2}\frac{R_i}{\nu\, B\, L_i}, \tag{14}$$

where: R_i – normal reaction of soil, influence on a wheel, N.

Adding the relation (13) we obtain with the formula (14) the element of the horizontal towing power as a shearing effect of soil:

$$P_{SD\,i} = (1-k_H)\frac{f_{\text{ск}} k_\partial R_i}{\delta\, L_i}\left\{\ln ch\left(\frac{\delta\, L_i}{k_\partial}\right) - f_{\text{пр}}\left[\frac{1}{ch(\delta\, L_i/k)} - 1\right]\right\}, \tag{15}$$

The element of the horizontal towing power resulting from the friction of a tyre tread on soil is [8]:

$$P_{\text{тр}\,i} = k_H\,\sigma_{cp\,i}\,\nu\, B_k L_i\,\mu_{\text{ск}}, \tag{16}$$

where: $\mu_{\text{ск}}$ – coefficient of a tyre tread friction on soil.

Coefficient of the slip friction depends on the slip speed and normal pressure on the place of a contact [13]:

$$\mu_{\text{ск}} = \mu_n + \left[\left(\mu_{\text{усл}} - U\,\sigma\right) - \mu_n\right]\left[1 - 1/\theta^n\right], \tag{17}$$

where: μ_n – coefficient of friction of the tyre tread on soil including slipping;

$\mu_{\text{усл}}$ – replacement coefficient of the tyre tread friction on soil at $\theta \to \infty$ and $\sigma \to 0$;

U - angular coefficient;

θ - coefficient of slip, $\theta = 1/(1-\delta)$;

n - parameter which depends on the type and condition of soil.

Relation (16) after including formulas (14) and (17) assumes the following form:

$$P_{\text{тр}\,i} = k_H R_i\left\{\mu_n + \left[\left(\mu_{\text{усл}} - U\frac{R_i}{\nu\, B\, L_i}\right) - \mu_n\right]\left[1-(1-\delta)^n\right]\right\}, \tag{18}$$

Substituting the relations (15) and (18) to the formula (10) we obtain the horizontal (tangent) towing power of the i-wheel,

$$P_{k\,i} = (1-k_H)\frac{f_{\text{ск}} k_\partial R_i}{\delta\, L_i}\left\{\ln ch\left(\frac{\delta\, L_i}{k_\partial}\right) - f_{\text{пр}}\left[\frac{1}{ch(\delta\, L_i/k_\partial)} - 1\right]\right\} + \\ + k_H R_i\left\{\mu_n + \left[\left(\mu_{\text{усл}} - U\frac{R_i}{\nu\, B\, L_i}\right) - \mu_n\right]\left[1-(1-\delta)^n\right]\right\}, \tag{19}$$

The relation (19) enables determination of the impact of the soil resistance force during shearing and friction of a tyre tread on soil on the horizontal (tangent) towing power. The following relation of forces is of a considerable importance for the wheel systems when each following wheel moves on the track of the previous one.

3. Research results

The impact of the tread shape was not included in the theoretical discussion. If tyres have extended treads, then the tracks after the first wheel are corrugated. After that the second wheel drives in the track of the first one, a specific work of crushing blocks of soil and then soil shearing under the angle vertically and horizontally is performed (formation of new blocks). In the experiments, it was found out that in a given case, the rolling resistance of the back wheel is higher than the previous one [9].

Let us consider the possibilities of developing a high towing force without formation of soil blocks. Wheel adhesion to soil is obtained during the wheel slip. The size of slip depends not only on the condition of the soil surface but also on the shape of the tyre tread. At the developed tread, the shearing surface of a wheel, at the specific slip, i.e. at shearing soil blocks, a relocation of a wheel takes place, mainly at the surface of the tread blocks. In this case, the element of the horizontal towing power resulting from the friction of a wheel on soil is less significant than the component of the force, resulting from the crushing resistance of soil in longitudinal direction. In the described case, a corrugated surface in the track of wheels occurs, which is an undesired phenomenon in case of a wheel suspension system when wheels move on the same track.

If a protector (tread) ensures high adhesion to soil, not as a result of shearing with a tread, but as a result of tread friction on soil, then elevations and holes in the driving wheel track may be prevented. The research shows that at the longitudinal shearing of a body on the soil surface, soil deformation, not only on the surface, but also on the sufficiently low depths of the soil layer, takes place. This in-depth deformation of soil influences the increase of the level stress at shearing. The relation of the tangent stress to the gradient of the relocation of the soil layer takes the following form:

$$\tau = \mu_\varphi \frac{ds}{dh} f(\sigma),$$

where: μ_φ – coefficient, which depends on the friction of soil particles one against another;

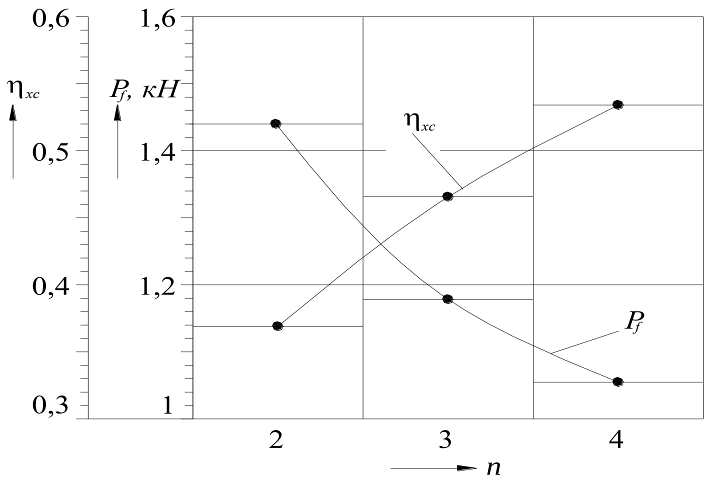
ds/dh – the gradient of the soil layer relocation in vertical direction;

$f(\sigma)$ – the function which determines the relation of the internal friction of soil on the stresses condition.

Experimental research of traction properties of soil of the multi-axle suspension system was carried out on the mechanical model in the soil channel [10]. Tyres 5.00-10 of driving wheels with an undeveloped tread were used.

Figure 1 shows that at the increase in the number of axles the rolling resistance decreases and the coefficient of operation performance of the suspension system increases. During the research, loading of the suspension system was constant and was 5.2 kN and pressures on soil were changing with an inversely proportional relation to the number of axles.

During the tests, we reported low values of the coefficient of operation performance of the suspension system ($\eta_{xc} = 0{,}51$). It may be explained with high losses related to deformation of the scarified moist soil and wheels with a small diameter and kinematic losses. After the increase of the wheels diameter to 1.5-1.8 m, the coefficient of operation performance of the suspension system increased to the value of 0.62 only as a result of limiting slips. Calculations were made pursuant to the probability criterion $\delta l/k_\partial$.



Source: own work / Źródło: opracowanie własne

Fig. 1. Relation of the rolling resistance and the coefficient of performance operation of the suspension system to the number of suspensions of the multi-wheel suspension system
Rys. 1. Zależność siły oporów przetaczania i współczynnika efektywności działania układu jezdnego od liczby podpór wielokołowego układu jezdnego

4. Conclusions

1. Increase in the number of axles of the multi-axle suspension system results in reduction in the rolling resistance of each subsequent wheel moving on the track of the previous one.
2. A chassis of multi-axle suspension systems should be equipped with tyres with a non-extended tread

5. References

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