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Reasoning a Construction Diagram and Parameters of Tillers for Primary Cultivation

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Abstract: Choosing a primary cultivation method for a particular soil and climatic zone depends on an adopted crop cultivation technology a type of cultivated crops, soil moisture and soil erosion susceptibility. Depending on these factors mouldboard and subsoil ploughing and their combinations are used. They are performed by different working bodies located on an implement frame in one or more row schemes as well as in the reversible wedge. Thus, reasoning a construction diagram of a tiller providing the lowest draught resistance and the highest operation rate for tractors of different drawbar category has practical importance. The study presents theoretical relationships to find draught resistance and gravity force for different construction diagrams of tillers as well as operation rate of farm machinery in different operation conditions and at different engine power of a tractor. The resulting third-order equation to define the operation rate of a machine is solved by the Cardano formula. There are resulting relationships that make it possible to find the operation rate of machinery when there is a change in a machinery motion speed and plow width of tillers made according to different construction diagrams. The received data helps engineers when designing implements to find rational values of a machinery speed, tiller plow width to justify their construction diagram that provides higher operation rate of machinery when working in different soil and climatic conditions.

Key words: Construction diagram, tillers, tractor engine power, specific metal content of a tiller, draught resistance, tiller plow width, machinery motion speed, operation rate

INTRODUCTION

Primary soil cultivation (mouldboard and subsoil tillage) is designed to get the required properties of the soil to cultivate crops in different soil and climatic conditions (Kozachenko, 2004; Zybalov *et al*., 2016; Rakhimov, 2016; Zybalov, 1999). Tillage is carried out by different types of working bodies with fixed parameters for a given soil type and a climate zone parameters. Ploughing is performed at a certain depth (0.2-0.3 m at the mouldboard ploughing, 0.2-0.45 m at the subsoil plowing) aimed to develop best conditions for growth and development of plants and improve soil fertility (Taskaeva *et al*., 2012; Mazitov *et al*., 2012; Bykh, 2010). It should be noted that working bodies made on various construction diagrams are mounted on the implement frame. The selected construction diagram of the implement must provide the desired quality of soil tillage, low draught resistance and high operation rate of the machinery. The solution of these problems is possible based on studies of the influence of various factors on the operation of tilling machinery (Bykh, 2010; Mudarisov *et al*., 2014; Spirin, 2006).

Scientists found that primary cultivation requires to be done in accordance with zone conditions, crops being planted and their place in crop rotation, implements for mouldboard and subsurface ploughing and soil chiseling. These implements are made according to different construction diagrams and have different metal content (Rakhimov *et al*., 2015). These factors influence on draught resistance and machinery performance (Goriachkin, 1965; Rakhimov *et al*., 2015; Sineokov and

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Panov, 1977). Relationships to determine metal content of an implement offered by Lurie and Lyubimov (1981) and Blednykh don't take into account operation conditions of a machinery and a construction diagram of an implement making it difficult to determine draught resistance and operation rate of the machinery.

Mileusniæ *et al*. (2010) depict obvious differences in energy consumption depending on crop production technologies. They offer a method to choose a better tractor for different soil tillage technologies.

Ranjbarian (2017) point out that energy conservation can be easily achieved by choosing energy-saving working bodies and proper matching dimensions and operating parameters of a tractor with implements.

The research of Ibrahmi *et al*. (2015) proves that there is a possible way to find the best combination of construction and technological parameters of a plow to reduce energy consumption.

Ibrahmi *et al*. (2015) argue in favour of higher plow draught resistance according to the second-order polynomial function due to increased depth while vertical and lateral forces have a linear relationship with depth. Moreover, these forces rise linearly with speed.

Hettiaratchi (1988) claims that destruction of the soil when stretched is an energy-saving way of soil loosening. Al-Kheer *et al*. (2011) were first to developed a reliable approach to the design of tillage machines. As the result a tiller design analysis included the force randomness in order to improve machine reliability. There is a conclusion on the way economic limitations integrated in the reliability approach can result in better tilling implements that provide the required level of reliability at low cost.

However, currently there is no mathematical model to justify rational parameters of plow width and machinery motion speed for different construction diagrams of implements providing higher operation rate of the machinery at different values of tractor engine power, specific resistance and tillage depth.

The research goal. Thus, reasoning a construction diagram of a tillage implement providing the lowest draught resistance and the highest operation rate for tractors of different drawbar category is acute and has practical importance.

MATERIALS AND METHODS

Primary cultivation is performed by wheeled or crawler tractors of different drawbar categories provided with tilling implements made according to different construction diagrams (Fig. 1). One- or more row plough schemas (Fig. 1b, c) with working bodies in the form of a symmetric wedge (Fig. 1a). In addition, these implements are equipped with rollers or other working bodies for surface tillage, mulching and levelling of the field surface.

Main indicators of tiller performance along with agro-technical indicators are draught resistance P, kN, operation rate of the machinery W, ha/h, being dependent on soil resistivity k, kN/m^2, tillage depth a, m, plow width B, m, operation speed V, m/sec as well as on the construction diagram of the implement and coefficients characterizing their metal content. Operation rate of the machinery W, ha/h is determined by the relationship:

$$W = 0.36Bv\tau \quad (1)$$

where, τ stands for a shift operation factor (τ = 0.7-0.9).

To achieve the highest performance of the machinery, you must select the correct combination of width and motion speed of the machinery at a known draught power N_{kp}, kW, found by the expression:

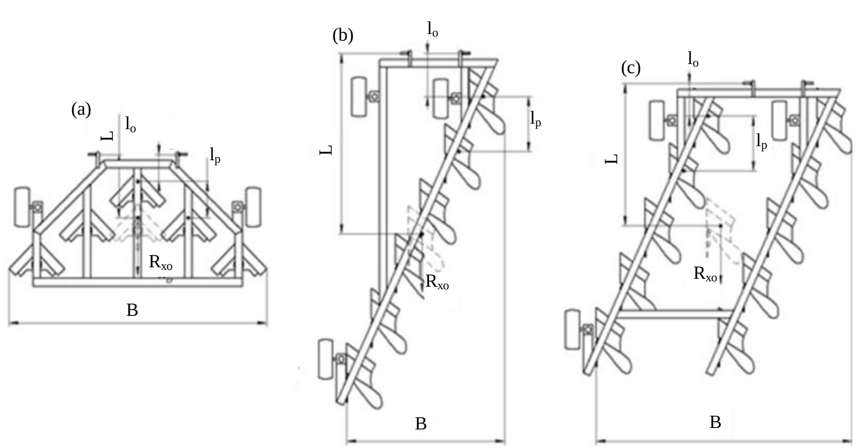

Fig. 1: a-c) Mounting arrangement of working bodies on the implement frame

$$N_{kp} = N_e \eta_T = P_{kp} V ИЛИ V = \frac{N_e \eta_T}{P_{kp}} = \frac{N_e \eta_T \eta}{P} \quad (2)$$

Where:

$P = P_{kp}\eta$ = Draught resistance of a tilling implement (kN)
P_{kp} = A draft force on a tractor hook (kN)
N_e = Stands for a tractor engine power (kW)
η = A draft force coefficient on a tractor hook ($\eta = 0.95$)
η_T = Wheeled tractor transmission efficiency ($\eta_T = 0.6$)

According to the formula of academician Goryachkin draught resistance of dual-purpose, combined implements in general is determined according to the following relationship:

$$P = fG_M + K_{1i}a_{1i}B + \varepsilon a_{1i}BV^2 + \sum_{i=1}^{n}(K_{2i}a_{2i}B) \quad (3)$$

Where:

G_M = Gravity force of a dual-purpose tiller with an installed type of work on (kN)
f = A resistance coefficient to pull a tiller ($f = 0.3$-0.5) Eq. 12-21
K_{1i} = Stands for soil resistivity to working bodies, kN/m^2 (K_{1i} = 40-70 kN/m^2) (Sineokov and Panov, 1977)
a_{1i} = Operation depth of working bodies, m (a_{1i} = 0.2-0.3 m at mouldboard ploughing and a_{1i} = 0.2-0.45 m at chisel tillage)
ε = The coefficient taking into account influence of motion speed, soil properties and shape of the working surface of the working body on the draught resistance, kHc^2/m^4 (ε = 1-2 kHc^2/m^4) (Sineokov and Panov, 1977)
K_{2i} = Soil resistivity of different types of additional working bodies (harrows, rollers, land levelers, etc.), kN/m^2 (K_{2i} = 15-25 kN/m^2)
a_{2i} = Stands for operation depth of additional working bodies, m (a_{2i} = 0.04-0.08 m)
n = The number of additional working bodies and devices operating simultaneously

Substituting the values of P and V from the Eq. 2 and 3 in Eq. 1, we have:

$$W = \frac{0.36 N_e \eta_T \tau \eta}{\frac{fG_M}{B} + K_{1i}a_{1i} + \varepsilon a_{1i}V^2 + \sum_{i=1}^{n}(K_{2i}a_{2i})} \quad (4)$$

Tiller gravity force (metal content) G_M, kN is determined by the following Eq. 5 and 6:

$$G_M = B\left[0.5\gamma_M S_0 + \beta a_{1i}K_{1i}L^2 + a_i a_{1i}K_{1i} + \sum_{i=1}^{n}(\eta_i a_{2i}K_{21})\right] \quad (5)$$

Where:

γ_M = Steel specific weight, kN/m^3 (γ_M = 78.5 kN/m^3); for mounted machinery γ_M = 0.22
S_0 = The total cross-section area of a drawbar hitch, m^2 (S_0 = 0.008 m^2)
β = Stands for specific metal content coefficient of implement frame structures, 1/m^2 (β = 0.02 and 0.011 for plows with single and double row arrangement of the working bodies, respectively, β = 0.039 and 0.02 for chisel implements)
L = The distance from the axis attaching the front frame bar to the mounting mechanism or device to the total force point taking into account the additional working bodies (m)
α_i = The coefficient of specific metal content of the working bodies (α_i = 0.13 for the plough body and α_i = 0.032 for chisel working body)
η_i = Stands for the coefficient of specific metal content of the additional working bodies or devices (η_i = 1.3 for chisel implements)

Applying the value of G_M from the Eq. 5 and 4, we have:

$$W = \frac{0.36 Ne \eta_T \tau \eta}{N+Z} \quad (6)$$

$$N = f\left[\beta a_{1i}K_{1i}L^2 + (\alpha_i a_{1i}K_{1i})\right] + a_{1i}K_{1i} + f\sum_{i=1}^{n}(\eta_i a_{2i}K_{2i}) \quad (7)$$

Where:

$$Z = \sum_{i=1}^{n}(a_{2i}K_{2i}) + \varepsilon a_{1i}V^2 + 0.5f\gamma_M S_0$$

This equation allows us to determine the performance of tillage tools, made on various construction diagrams (plow, wedge, taken into account through the L parameter), under different operation conditions (a_{1i}, K_{1i}, a_{2i}, K_{2i}, ε, τ) given their metal content (coefficients β, α_i, η_i) at changes N_e, B and V.

RESULTS AND DISCUSSION

To use construction diagrams of implements in Eq. 7, we express the L parameter through the construction parameters of implements. Then the value of L is as follows: For implements made by the plow diagram (Fig. 1):

$$L = l_o + \frac{0.5 l_p (B - b'c_2)}{b'c_2} \quad (8)$$

Where:

- l_0 = The distance from the axis attaching to the mounting mechanism or device to the center of resistance of the first working body or the first row of the working bodies (m)
- l_p = The distance between the working bodies as viewed in the direction of the machinery motion, m (l_p = 0.7-1.0 m)
- b' = The distance between the traces of the working bodies, m (b' = 0.35-0.5 m)
- c_2 = Stands for the number of sections of the working bodies on the frame, pcs (c_2 = 1.2, etc.)

For plows with $l_0 = 0.5\ l_\delta = b'$ L = B/c_2. Then for single-section arrangement of the working bodies (c_2 = 1) L = B and for two-section arrangement (c_2 = 2), L = 0.5 B, etc. For implements, made with working bodies arranged in the form of a symmetric wedge (Fig. 1):

$$L = l_o + 0.25 l_p \left(\frac{B - b'}{b'}\right) \quad (9)$$

For implements with $2l_0 = b' = 0.5\ l_\delta$ L = 0.5 B. Let's take the L parameter in the form:

$$L = MB \quad (10)$$

where, M = 1; 0.5; 0.33; 0.25, respectively for the plough system of one-two-three-four-part arrangement of working bodies; Whereas, the Eq. 1:

$$B = \frac{W}{0.36V\tau} \quad (11)$$

Then:

$$L = \frac{MW}{0.36V\tau} \quad (12)$$

Let's use the value L from Eq. 12 in and present an Eq. 6 in the form:

$$W^3\mu + W_\gamma - N_e = 0 \quad (13)$$

Where:

$$\mu = \frac{f\beta a_{1i} K_{1i} M^2}{AC^2V^2}$$

$$\gamma = \frac{1}{A}\{fa_i a_{1i} K_{1i} + a_{1i} K_{1i} + \varepsilon a_{1i} V^2 + f\sum_{i=1}^{n}(a_{2i} K_{2i} \eta_i) + \sum_{i=1}^{n}(a_{2i}(K_{2i}) + 0.5 f\gamma_M S_0\}$$

Denote $\gamma/\mu = 3p$ and $N_e/\mu = -2g$; Then an Eq. (13) takes the form:

$$W^3 + 3pW + 2g = 0 \quad (14)$$

The solution of Eq. 14, we find by the Cardano Eq. 23 in the form:

$$W = z - u \quad (15)$$

Where:

$$z = \sqrt[3]{-g + \sqrt{g^2 + p^3}} \quad (16)$$

$$u = \sqrt[3]{g + \sqrt{g^2 + p^3}} \quad (17)$$

The functions g and p will be written using the reference data:

$$g = -\frac{N_e}{2\mu} = -\frac{N_e V^2 (0.36\tau)^3 \eta_T \eta}{2f\beta a_{1i} K_{1i} M^2} \quad (18)$$

$$p = -\frac{\gamma}{3\mu} = \frac{V^2C^2}{3f\beta a_{1i} K_{1i} M^2}\{f a_1 a_{1i} K_{1i} + a_{1i} K_{1i} + \varepsilon a_{1i} V^2 + f\sum_{i=1}^{n}(a_{2i} K_{2i} \eta_i) + \sum_{i=1}^{n}(a_{2i} K_{2i}) + 0.5 f\gamma_M S_0\} \quad (19)$$

The dependences Eq. 15-19 make it possible to calculate operation rate W for all types of tillers (mouldboard, subsurface working bodies or their combinations, different arrangement schemes of the working bodies on the implement frame) depending on the operating speed for all brands of tractors at work in various conditions. It is necessary to specify initial data corresponding to the conditions of operation of the unit.

Similarly, we define the dependence of the performance of the unit from the width V. To do this, we find from the Eq. 1:

$$V = \frac{W}{0.36B\tau} \quad (20)$$

Substitute the value L from the Eq. 10 and the value V from the Eq. 20 in the Eq. 6 and present the equation in the form Eq. 14. The solution of the Eq. 14 has the form presented in Eq. 15-17. We write the functions g and p using the initial data:

$$g = -\frac{N_e}{2\mu} = -\frac{N_e AC^2B^2}{2\varepsilon a_{1i}} = -\frac{N_e B^2 (0.36\tau)^3 \eta_T \eta}{2\varepsilon a_{1i}} \quad (21)$$

$$p = -\frac{\gamma}{3\mu} = \frac{B^2(0.36\tau)^2}{3a_{1i}}\{a_{1i} K_{1i} + \sum_{i=1}^{n}(a_{2i} K_{2i}) + 0.5 f\gamma_M S_0 + f[\beta a_{2i} K_{2i} (MB)^2 + a_1 a_{2i} K_{2i} + \sum_{i=1}^{n}(a_{2i} K_{2i} \eta_i)]\} \quad (22)$$

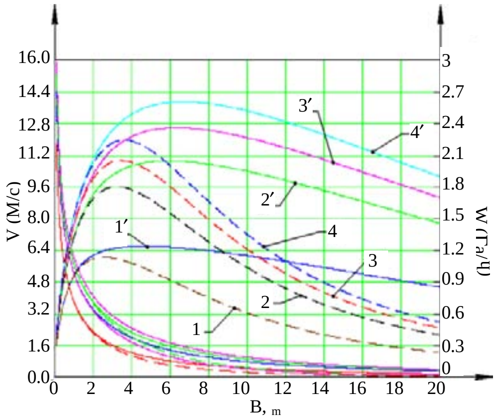

Fig. 2: Dependence of the unit motion speed V and operation rate W on tiller plow width for mouldboard ploughing B at different values of engine power of the tractor Ne

The dependences Eq. 21 and 22 present operation rate of units at various values of the plow width of implements and their working conditions.

According to the calculation results a tiller construction diagram is chosen for a particular tractor. This diagram provides better operation rate at rational combinations of width and speed of the unit when tillage under the same agro-technical parameters.

In calculations we take the following values of engine power: N_e = 128 kW for third-class tractors, N_e = 220 kW for fifth-class tractors, N_e= 257 kW for sixth-class tractors, N_e = 287 kW for eighth-class tractors.

As an example, Fig. 2-4 present the results of calculations for mouldboard tillage implements with working bodies arranged in one or two rows:

- 1, 2, 3, 4: single-row arrangement of the working bodies
- 1', 2', 3', 4': two-row arrangement of the working bodies
- 1, 1': Ne = 1287 kW; 2.2': Ne = 220 kW; 3.3': Ne = 257 kW; 4.4': Ne = 287 kW
- a = 0.35 m, K = 40 kH/M^2, ε = 1 kH.c^2/M^4, f = 0.3, l_p = 0.7 m, η = 0.95, $\eta_{T\ddot{o}}$ = 0.60

The unit motion speed V, plow width B and unit operation rate W are mostly influenced by the engine power of the tractor N_e (Fig. 2), the soil resistivity K (Fig. 3) and soil tillage depth a (Fig. 4). When N_e operation rate W and rational values of plow width B increase and the value of speed V decreases. On the contrary, If K rises the rational values W and B lowers and V increases. In all cases two-row arrangement of the working bodies on the implement frame provides higher rational values of the width B due to the reduced metal content of the implement frame (reduced distance L). It results in higher operation rate of the unit W where the W and B value area increases:

- 1, 2, 3, 4: single-row arrangement of the working bodies
- 1', 2', 3', 4': two-row arrangement of the working bodies
- 1.1': K = 40 kH/M^2; 2.2': K = 50 kH/M^2; 3.3': K = 60 kH/M^2; 4.4': K = 70 kH/M^2

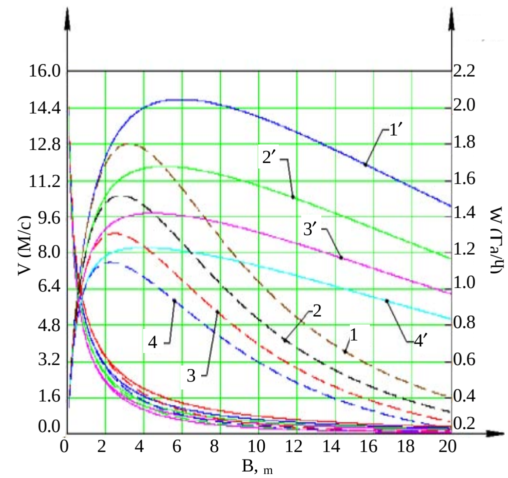

Fig. 3: Dependence of the unit motion speed V and operation rate W on tiller plow width for mouldboard ploughing B at different values of soil resistivity K

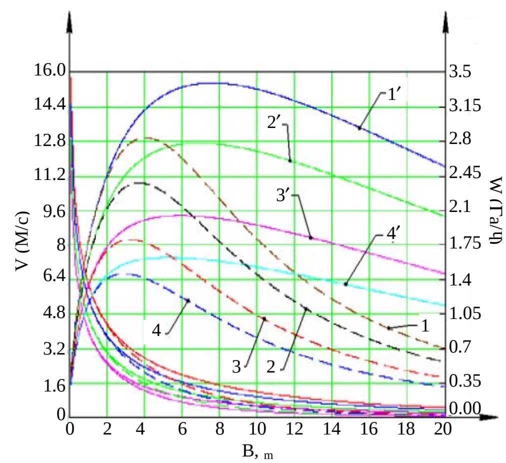

Fig. 4: Dependence of the unit motion speed V and operation rate W on tiller plow width for mouldboard ploughing B at different values of tillage depth a

- (Ne = 220 kW, a = 0.35 m, ε = 1 kH.c²/M⁴ f = 0.3, l_p = 0.7 m, η = 0.95, η_T = 0.6)
- 1, 2, 3, 4: single-row arrangement of the working bodies
- 1', 2', 3', 4': two-row arrangement of the working bodies
- 1.1': a = 0.2 m; 2.2': a = 0.25 m; 3.3': a = 0.35 m; 4.4': a = 0.45 m
- (Ne = 220 kW, K = 40 kH.c^2/M^4, ε = 1 kH.c^2/M^4 f = 0.3, l_p = 0.7 m,η = 0,95,η_T = 0.6)

This proves that the correct choice of the construction diagram of an implement (by increasing the number of rows to arrange working bodies) can reduce the metal content of the implement, increase operation rate of the unit and reduce costs on primary cultivation.

The change in the resistance coefficient f has an impact on the values of V, W and B mostly beyond their rational values. When f raises, rational values W and B decline while V increases.

The influence of the coefficient ε is more essential to achieve rational values of width B and operation rate W. Higher ε decreases operation rate of the unit and increases the rational values of width. The obtained data show the need for proper choice of parameters and the location of support wheels to reduce the coefficient f and parameters of the working body to reduce the coefficient ε. Increased shift operation factor τ leads to a higher operation rate of the unit.

Rational values of the plow width B to provide better operation rate of the unit W can be determined if the tractor engine power N_e and the specific conditions of the zone where the implement is to be used (soil resistivity K and tillage depth a) from the presented dependences (Fig. 2-4) are known.

Similar calculations were made for implements with chisel working bodies. Compared to the mouldboard ploughing at the depth a = 0.2 m the chisel tillage at the depth a = 0.35 m reduces the rational values of the width B and operation rate of the unit W by 50-60%.

Thus, the conducted research and the proposed method to justify construction diagrams and parameters of tillers for primary cultivation taking into account soil resistivity and tillage help to determine rational parameters of width and motion speed of a tractor of any draught class. It ensures better performance of tillers.

This allows designers to develop tillage machines with rational parameters adaptable for all soil-climatic zones, brands of tractors and work environment that expands knowledge in this area.

In contrast to the results of other researcher discussed above, this paper deals with research results that were obtained, taking into account all the factors affecting the draught resistance and operation rate of the unit (soil properties, working depth, tractor power, construction diagram of implements their metal content, plow width, motion speed and coefficients characterizing the type of working bodies). Nevertheless, the way draught resistance of an implement as well as operation rate of the unit change is the same as it was found by other researchers that proves reliability of the received results.

CONCLUSION

The scientific value of the research is that it reveals the relationship of draught resistance of tillers and operation rate of the unit with soil properties, tillage depth and construction diagram of an implement its metal content, plows width, the unit motion speed and coefficients that characterize the type of the working body. The given method to justify a construction diagram of an implement with rational parameters of the plow width and motion speed of the unit, providing better performance under different soil properties, metal content of an implement, tillage depth and engine power of a tractor proves to be new and can be recommended to designers to develop tillage implements for different soil and climatic zones.

There is a new mathematical model to justify rational parameters of plow width and machinery motion speed for different construction diagrams of implements providing higher operation rate of the unit at different values of tractor engine power, specific resistance and tillage depth.

Rational parameters of different construction diagrams for primary cultivation tillers with single-row and two-row arrangement of working bodies on the implement frame are found. The ways to reduce draught resistance of implements and increase operation rate of units are determined. The developed method to reason parameters of implements and their resulting rational parameters can be used by designers to develop similar tools.

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