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2D Analytical Model for Evaluation of the Forces in the Three-point Hitch Mechanism

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ABSTRACT

Large investments, research efforts and time have been allocated till nowadays for innovation of agricultural tractors and machinery, with the primary aim to increase their productivity, reliability, durability, as well as the environmentally friendly, safe and easy usage. Following this general trend, present work is focused on theoretical analysis of the forces acting on the links of the three-point hitch mechanism. The simulation algorithm and computer code have been developed for calculation of draft forces by two methods (following ASAE D497.4 standard and Goryachkin approach), depending on the

three point linkage geometry and mouldboard technical characteristics, and calculation of forces acting on lower and upper links of three-point hitch mechanism. Calculated forces values, based on ASAE draft, exposes smaller differences compared to experimental values, while for the Goryachkin method improvement is possible by entering experimental values for soil resistance coefficient k and coefficient of dynamic resistance ϵ , as we did in this study performing measurements on the aggregate comprehending tractor IMT 539 (IMT Belgrade, Serbia) and two furrow moldboard plough PTO 2.25 (OLT, Osijek, Croatia).

Keywords: Three hitch point; Tractor; Draft; Link forces

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1. Introduction

Nowadays, large funds are allocated for innovation of agricultural tractors with the primary aim to increase their productivity, reliability, durability, as well as the safe and easy usage (Mileusnić et al 2010). Arizton Advistory & Intelligence (2018) indicates that the number of low-power tractors participate a third of total sales in 2017., having the approximate growth of 5% in some developed countries and in emerging ones in forecast period 2018-2023. Generally, about 84% of existing farms possesses less than 2 hectares, comprehending 12% of agricultural land, and even more in the less developed countries (Sarah et al 2016). Lower price, simplicity and functionality motivate owners of small farms to buy tractors with lower installed power, what was a motive to base present study on a low-power tractor.

Agricultural tractors are driving units with a wide range of possible implementations in agriculture, forestry etc. In order to provide possibility of tractors connecting with various implements applied, most of tractors are equipped with a three-point hitch mechanism (TPH). Many studies on TPH mechanisms were focused on the forces transition between tillage implements and tractors, which has the crucial influence on the operational efficiency and energy management (Dalmiș et al 2017), as we did here.

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After introducing the hydraulic system for position control, three-point linkage was improved and still remains in use in the low-power, but also in the high-power tractors. Therefore, standards recognizing four categories of these mechanisms were introduced to provide adjusting of their design to tractors having various power and traction forces.

This paper presents an analytical approach for identifying forces of three point hitch mechanism components based on the known geometry, mechanism working position, soil resistance and plough characteristics. Special computer code has been formulated, based on field measurements on the experimental parcel with known plough geometry, for assessment of forces acting on the links of the three point hitch mechanism.

During operation, the three-point linkage transfers forces acting on the implement to the tractor. Ploughing is a highly power demanding soil tillage operation (Fröba 1995), comprehending cutting and turning up and over the surface soil layer enriched with minerals and decomposed organic matter, usually in the depth range of 15÷30 cm. Going deeper increases the soil resistance and consumed energy. Beside the ploughing depth, soil reactions toward plough depend on the plough design, mechanical and other soil physical parameters and the tractor speed.

2. Material and Methods

2.1. The analytical model

Forces acting on the plough can be represented with three-dimensional force vector acting on the pull center. This is not a fixed point because of the soil parameters variability, settings of the plough and connectivity with three point linkage. The lateral R_z force is counteracted by a landside force. The vertical force R_y results from the weight of the plough body, weight of the soil volume lifted by the moldboard and vertical soil force. Part of R_y may be also supported by gauge wheel. The longitudinal force, so-called *draft resistance* R_x , is the rearward soil force component, that must be overcome by tractor power. Dominant soil mechanical parameters influencing R_x are the soil deformation resistance and friction. The soil mechanical parameters changes with variations of soil texture and moisture content over depth (Haines 1925), affecting the forces acting on the links of three-point mechanism.

Variability of the soil properties imposes hard difficulties in the formulation of the general equations for the draft resistance evaluation. Draft resistance can be analytically estimated following standard ASAE (2003) Standard D497.4, 2003, and Goryachkin's formula defined as a sum of static resistance and a dynamic resistance (Горячкин 1968)

$$R_x = G \cdot f + k \cdot a \cdot b \cdot n + \varepsilon \cdot a \cdot b \cdot n \cdot v^2 \quad (1)$$

Where; G (N) is the plough weight; f (-), represents the friction coefficient over the working element surface; k (N m⁻²) is the specific soil resistance; a (m), designates the ploughing depth; b (m) is the width of ploughing tool; n is the number of tools; ε (Ns² m⁻⁴), represents the coefficient of dynamic resistance, and v (m s⁻¹) is tractor velocity.

The plough friction coefficient usually has a value 0.3÷0.5 (Bernacki et al 1972), but in compact soil has a greater value.

The second member of equation corresponds to the energy used to cut and deform the slice of soil. Soil resistance coefficient k is a function of soil type, depth, humidity, the presence of crops or residues etc. Consequently, an experimental approach was needed.

The third term corresponds to energy required for movement the slice of soil over the mouldboard and for its throwing aside. The coefficient of dynamic resistance ε depends on tractor speed and shape of the mouldboard body. Its value ranges between 3000 and 10000 Ns² m⁻⁴ (Musil & Červinka 2007).

In the Expression (1), influence of plough geometry on draft resistance is also given by its width b . For more accurate determination of plough geometry influence, an experimental approach is needed (Plouffe et al 1995).

According to ASAE Standard D497.4 draft resistance can be described by the formula

$$D = F_i \cdot [A + B \cdot s + C \cdot s^2] \cdot W \cdot T \quad (2)$$

Where; F_i is parameter of soil texture ($i= 1, 2, 3$ for fine, medium and coarse texture respectively), A, B, C are the machine parameters (for moldboard plough $A= 652, B= 0, C= 5.1$), W (m) represents machine width or number of tools, T (cm) is the tillage depth, s (km h^{-1}) designates tractor velocity. This standard provides a good estimate of average implement draft. However, changes in ground profile, soil texture and tractor ride dynamics may lead to draft amplitude of up to $\pm 50\%$ (McLaughlin et al 2008).

The three point linkage is a 3D mechanism, consisting of the upper link, two symmetric lower links with lift rods, rockshaft arm and corresponding pins. Top and lower link set up implement into the right working position. Built in control system allows control of the implement position and/or draft force.

Fully mounted implement carries over forces to the three-hitch point. The intensity of the force depends on the position of hitching point and length of the links. Variations of the force in upper link with its length were shown by Čupera et al (2011). Tractor manufacturer usually has a test report of link length and pivot point position, measured from the rear wheel axis center. Side view of three point linkage with example of its dimensions is presented in Figure 1a. The goal of present study was to estimate forces acting on the three hitch point. Background data includes known three point linkage geometry (l_1 – l_6) and position (α_1 – α_5), estimated soil resistance (R_x, R_y, c_1, c_3), plough weight (G, c_2) and tractor rear-wheel radius (R). Position of three point linkage is determined by ploughing depth. It is not necessary to measure distance from all hitch points to the ground, but only the distance from lower link to the ground l_7 , because the mast height l_6 is already known, Figure 1b. Equations (3)–(7) were developed to determine three point positions with input data presented in Figure 1a.

$$\alpha_1 = a \sin Q_5 \quad (3)$$

$$\alpha_2 = \arccos \left[\frac{(l_4^2 + Q_1 + l_2^2 - 2 \cdot Q_1^{1/2} \cdot l_2 \cdot \cos(\pi + \arctan Q_2 + \arcsin Q_3) - l_3^2)}{(2 \cdot l_4(Q_1 + l_2^2 - 2 \cdot Q_1^{1/2} \cdot l_2 \cdot \cos(\pi + \arctan Q_2 + \arcsin Q_3))^{1/2})} \right] + \arccos \left[\frac{(l_2 - Q_1^{1/2} \cdot \cos(\pi + \arctan Q_2 + \arcsin Q_3))}{(Q_1 + l_2^2 - 2 \cdot Q_1^{1/2} \cdot l_2 \cdot \cos(\pi + \arctan Q_2 + \arcsin Q_3))^{1/2}} \right] \quad (4)$$

$$\alpha_3 = \arccos \left[\frac{(l_6^2 + l_5^2 - Q_4 - l_1^2 + 2 \cdot Q_4^{1/2} \cdot l_1 \cdot \cos(\arctan Q_5 + \arcsin Q_3))}{(2 \cdot l_5 \cdot l_6)} \right] \quad (5)$$

$$\alpha_4 = \arccos \left[\frac{(l_1 - Q_4 \cdot \cos(\arctan Q_5 + \arcsin Q_3))}{(Q_4 + l_1^2 - 2 \cdot Q_4^{1/2} \cdot l_1 \cdot \cos(\arctan Q_5 + \arcsin Q_3))^{1/2}} \right] + \arccos \left[\frac{(l_6^2 - l_5^2 + Q_4 + l_1^2 - 2 \cdot Q_4^{1/2} \cdot l_1 \cdot \cos(\arctan Q_5 + \arcsin Q_3))}{(2 \cdot l_6 \cdot (Q_4 + l_1^2 - 2 \cdot Q_4^{1/2} \cdot l_1 \cdot \cos(\arctan Q_5 + \arcsin Q_3))^{1/2})} \right] \quad (6)$$

$$\alpha_5 = \alpha_1 + \alpha_4 - \frac{\pi}{2} \quad (7)$$

Where; $Q_1 = (x_2 - x_1)^2 + (y_2 - y_1)^2$; $Q_2 = \frac{y_2 - y_1}{x_2 - x_1}$; $Q_3 = \frac{R - l_7 + y_1}{l_1}$; $Q_4 = (x_3 - x_1)^2 + (y_3 - y_1)^2$; $Q_5 = \frac{y_3 - y_1}{x_3 - x_1}$;

Vertical component of soil force for moldboard can be related with draft force (Martinov & Marković 2002):

$$R_y \approx 0.14 R_x \quad (8)$$

Depending on the plough design, the vertical component of soil reaction force may be supported by the gauge force, landside heel or may be completely transferred to the three point linkage. The center point of soil resistance T_4 on a mouldboard plough is located halfway along the slice width and one-third of the ploughing depth by Bernacki & Haman (1967), while Wilkinson & Braunbeck (1977) placed center of soil resistance on one-fourth of the slice width from landside and one-fourth of the ploughing depth.

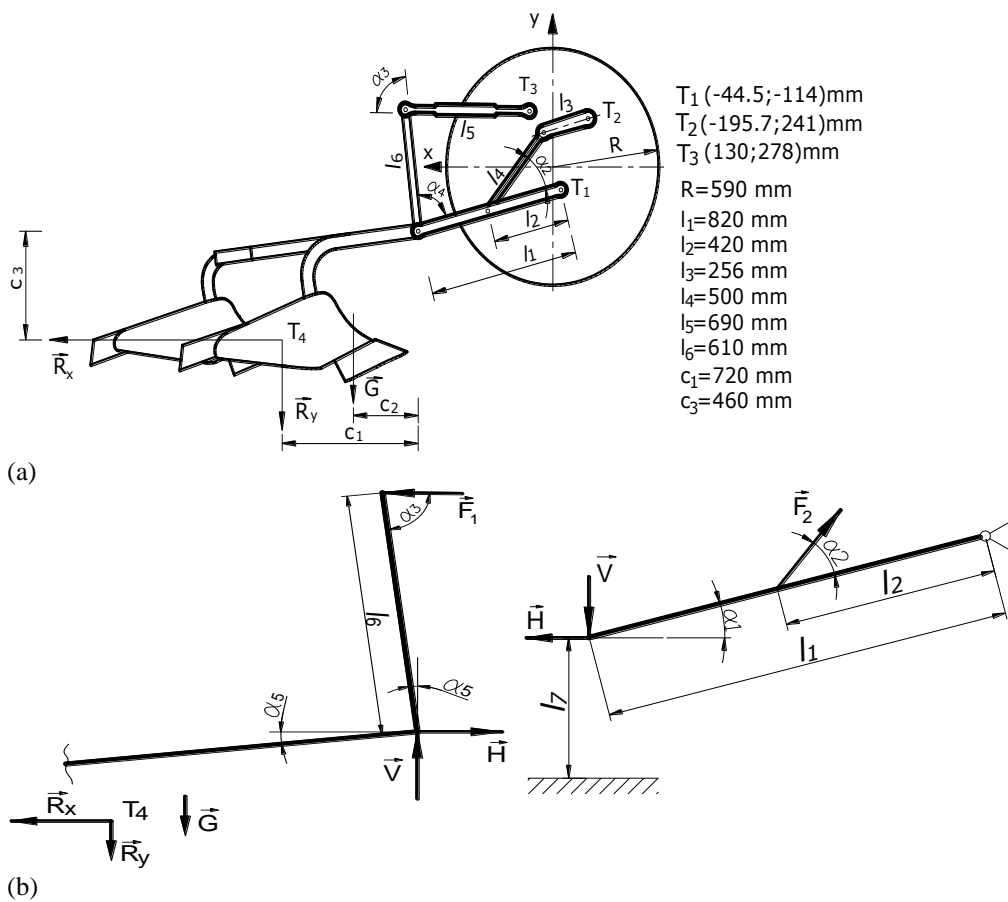


Figure 1- Three point linkage mechanism: a, three point linkage geometry; b, position of mast and lower link, and forces acting on these elements, during ploughing with forces

Implement motion is limited by three-point linkage, except it has freedom to rise up. By knowing the moving pattern (Equations (3)-(7)), it is possible to calculate forces acting on the three hitch point for each working position. The calculations only take into account the simplified 2D model of loading. Loading scenario for the mast and lower link is presented in Figure 1b. Uniform motion of tractor is assumed in this analysis, so there is no inertial force. Newton’s second law gives three independent equations of equilibrium needed to determine the forces acting on the mast.

$$F_1 = (R_x \cdot c_3 - 0,1 \cdot R_x \cdot c_1 - G \cdot c_2) / (l_6 \cdot \sin(\alpha_3)) \tag{9}$$

$$H = (R_x + F_1 \cdot \sin(\alpha_3 + \alpha_5)) / 2 \tag{10}$$

$$V = (G + 0,1 \cdot R_x - F_1 \cdot \cos(\alpha_3 + \alpha_5)) / 2 \tag{11}$$

Where; \vec{F}_1 is the force acting on upper link hitch point, while H and V are horizontal and vertical component of force acting on both lower link hitch point.

2.2. Experimental procedure

Tractor IMT 539 (IMT-Belgrade, Serbia) was used in the experiment, Figure 2a. Technical characteristics of this tractor were: Diesel engine power 29.5 kW, the mass 1789 kg, front wheels 6.00-16’’ and rear wheels 11.2-28’’. Implement used for ploughing was two furrow semi digger moldboard plough PTO 2.25 (OLT-Osijek, Croatia), with operating width 30 cm per each moldboard and total mass 215 kg, Figure 2b. The lower link was 820 mm long with eyebolts end. It was a lower link of the first (I) category.

A field test and measuring were conducted on the flat horizontal parcel, characterized by black soil type-chnozem consisting of 35% sand, 35% silt and 30% clay, soil moisture content was 19%, volume weight 1.47 g cm^{-3} . There were remains in the ground after harvest of wheat grains.

Force was measured using custom-made force transducer based on the strain measurements using strain gauges and calibration of the developed transducer. Used strain gauges, of commercial type 3/120KY31, manufactured by Hottinger Baldwin Messtechnik, Germany, were mounted as it is explained in Cerović et al (2018), Figure 2c. Measuring resistance of these gauges are $120 \Omega \pm 1\%$, measuring grid length 3 mm, code number for the temperature response for ferritic steel $\alpha = 10.8 \cdot 10^{-6} \text{ K}^{-1}$, maximum bridge excitation voltage 8 V, transverse sensitivity 0.1%, gage factor $2.00 \pm 1\%$. Lower link of the mechanism was equipped with strain gauges as shown in Figures 2d, 2e. Prior to measurement, calibration of the lower link was performed, (Figure 2f) and dependence between the applied force and strain measurements was estimated using coefficient $0.0785 \text{ kN } \mu\text{m}^{-1}$, reaching the R-square value of $R^2 = 0.9996$, Figure 2g. Calibration was performed in the same position as the lower link is mounted on the tractor and with a depth corresponding to middle of the range of depth selected during the experiment. Force was measured using force transducer HBM U5 200 kN connected with DAQ system Quantum MX840A, (Figure 2h). Strain gauges applied on the lower link were connected in to Wheatstone bridges in order to measure horizontal force and bending caused by link geometry and consequently by eccentricly acting of forces on the link joints. Power supply for DAQ system was realized using petrol generator HONDA EU10i.

After analysing the calibration data and findings of Cerović et al (2018), it was noticed that due not only the pure axial load of the lower link but also the bending moment around the vertical axis, it is better to use (mount) only longitudinal strain gauge. Due to loading direction which does not coincide ideally with the axis, transversely placed strain gauge impose an error in establishing a connection between loading and relative deformations of the strain gauge. In order to have more accurate measurements, additional sensors should be added to measure forces in all mechanism components.

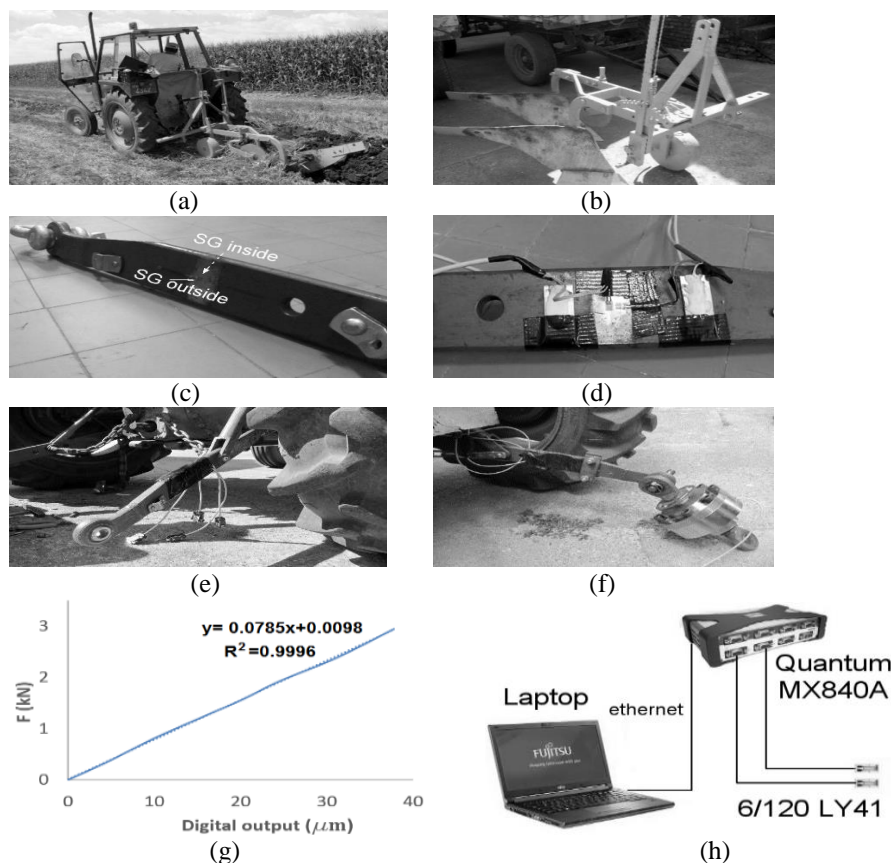


Figure 2- Experimental set-up: a, tractor in the test plot; b, two furrow moldboard plough; c, strain gauges position; d, strain gauges; e, mounting configuration directly on the lower link; f, field calibration; g, calibration line of lower link; h, measuring chain

Different ploughing depths and velocities were chosen in the field experiments, according tractor power and plough specification, Table 1.

Table 1- Ploughing depth and velocity chosen for experiment

Measurement	1	2	3	4	5	6	7	8	9
Depth (cm)	20	20	20	17	15	13.5	11	11	15
Velocity (km h ⁻¹)	2	4	6	2	2	2	2	6	6

The plough was set in accordance with agro-technical requirements during all measurements. The tractor passed 50 m in each measurement. Measurements were repeated three times.

3. Results and Discussion

Measured values are shown in Figure 3. Recorded values of the measured forces showed strong fluctuations, which are mainly caused by the variations of soil resistance. Skalweit (1952) pointed out that ploughing depth tolerance should be $\pm 10\%$ of the mean value when the ploughing depth is about 18÷25 cm. Changes in ground profile and soil structure lead to variability of the measured forces. Experimentally obtained values, Figure 3, indicate a change of horizontal force in lower link with depth and velocity. Descriptive statistics of all measurements are presented in the Table 2. Such dependence is also noticeable in both formulas for soil resistance calculation, Equation (1) and Equation (2). As the soil type affects soil resistance, it is an essential factor of equations, although the ASAE D497.4 method is somewhat simpler than the Goryachkin method. Necessary parameters of soil type and machine are given in ASAE standard. Goryachkin method is based on experimental data. Yet, some regularity was noticed for specific soil resistance coefficient k : 20÷40 kN m⁻² for light soils (sandy, silt); 40÷60 kN m⁻² for medium soils (sandy clay); 60÷80 kN m⁻² for heavy soils (clay) and 80÷100 kN m⁻² for very heavy soils (Martinov & Marković 2002).

Test field chernozem is medium soil type. The third member of the equation (1) does not exceed 5% of total draft force (Borissov 2007) and therefore can be neglected. For the test, chosen value for coefficient of dynamic resistance ϵ was 3 kNs² m⁻⁴. Next assumption for Goryachkin method was the value of 0.3 for the friction coefficient. After entering all data in Goryachkin Equation (1), it became obvious that the second term of the formula is dominant for small working velocity.

Based on Eqs. (1)÷(11) and presented data, the computer algorithm was developed for approximate calculation of average longitudinal and vertical forces in the lower link and force in the upper link, Figure 4. An important role in the transfer of forces acting on a plough onto the links has the links geometry and position. Lengths of all links and pivot point position (sketched in the Figure 1a) were entered into the Fortran program (Adams et al 1997). After the position of links were calculated according to Eqs. (3)÷(7), the program prompts how to calculate the draft: only by Equation (2) or by both Equations (1) and (2). Applied Eqs. (8)÷(11) gave a simplified solution for forces.

The program has a loop for estimation of average horizontal and vertical forces acting on the lower link and force acting on the top link for different soil depths and tractor velocities. Horizontal and vertical force dependence on the tillage depth and working velocity is presented graphically in Figure 5, while Figure 6 displayed top link force change with soil depths and tractor velocities. In the Table 2 is presented the difference between measured and the calculated values for the H horizontal component of force acting on the lower link hitch point. As mentioned, the ASAE standard indicates that difference up to 50% is possible between measured and calculated values for draft, and therefore for H as its major part.

Calculation based on ASAE method for draft determination is easier to apply because of small number of input data. Goryachkin method can also be used for approximate calculation, but for more precise value of soil resistance the experimental values of input data are needed. Developed computer program gives approximate values for observed forces, which in real condition change on the same field because of soil texture, compaction, moisture, etc. Draft can vary from 30 to 200% (Morling R W 1979). Forces in the lower left and right link are different as well. Thus, the written program can be used to estimate the average values in links of three point hitch mechanism.

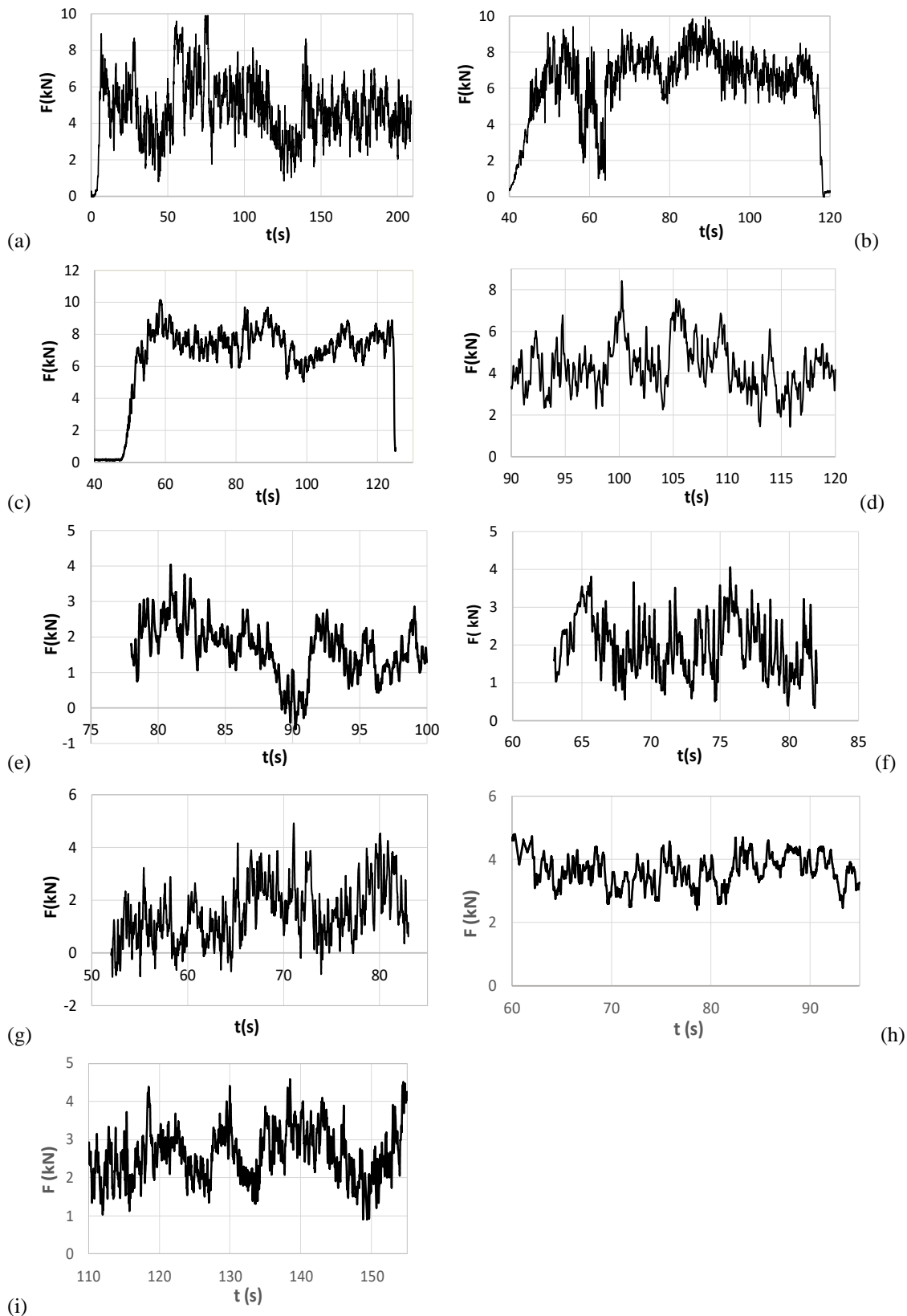


Figure 3- Sample of acquisition system data recorded for different depths and velocities. Sample measurement No.: (a) 1; (b) 2; (c) 3; (d) 4; (e) 5; (f) 6; (g) 7; (h) 8 and (i) 9, according to experimental plan listed in Table 1

Table 2- Statistical description of measurement in Table 1

Measurement	1	2	3	4	5	6	7	8	9
Mean	4.8214	6.8400	7.5448	3.7706	2.5817	2.1914	1.7851	2.7027	3.6484
Standard error	0.0045	0.0068	0.0042	0.0063	0.0052	0.0044	0.0042	0.0048	0.0037
Median	4.6847	7.0145	7.5664	3.7729	2.3598	2.0921	1.6675	2.6573	3.6712
Mode	5.0570	6.4582	6.5603	4.2563	2.1485	1.7798	1.3039	1.1135	4.3490
Standard deviation	1.5632	1.4132	0.8679	1.9661	1.3629	1.2014	1.1045	0.9894	0.76806
Sample variance	2.4436	1.9973	0.7533	3.8659	1.8576	1.4434	1.2199	0.9789	0.58991
Kurtosis	0.3803	2.6026	0.0281	-0.723	0.6122	1.7088	-0.2205	-0.1901	-0.1686
Skewness	0.5081	-1.273	-0.025	0.1485	0.8008	0.6429	0.353	0.1411	-0.1615
Range	9.0881	9.0205	5.1049	10.378	9.7101	9.4947	6.737	5.2350	3.33323
Minimum	0.8081	0.9292	5.0466	-1.098	-0.948	-1.228	-1.5002	0.2399	1.86605
Maximum	9.8962	9.9498	10.151	8.8800	8.7619	8.2658	5.2369	5.4749	5.19929

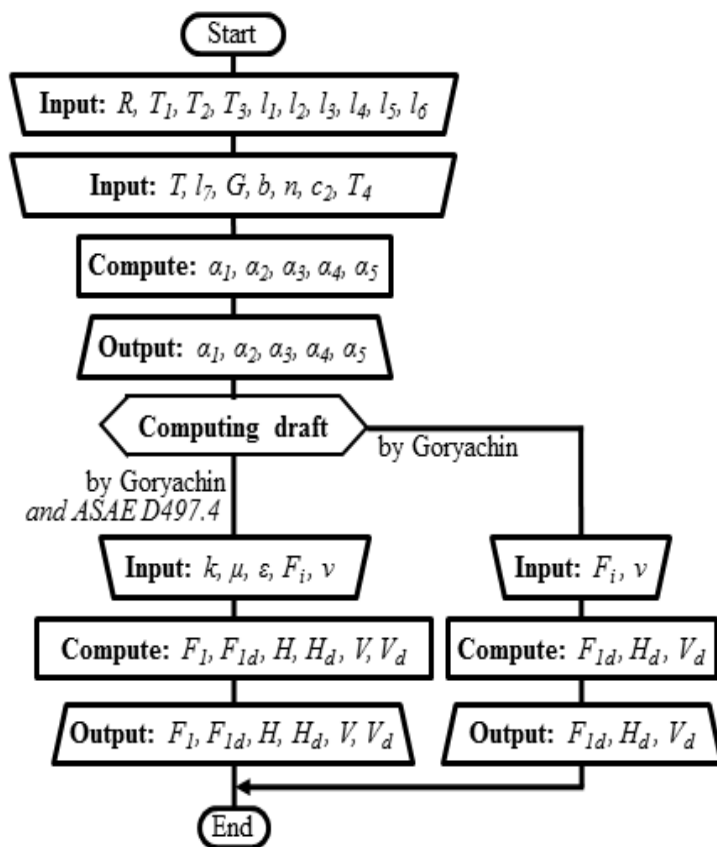


Figure 4- Block diagram representing the algorithm of the computer program

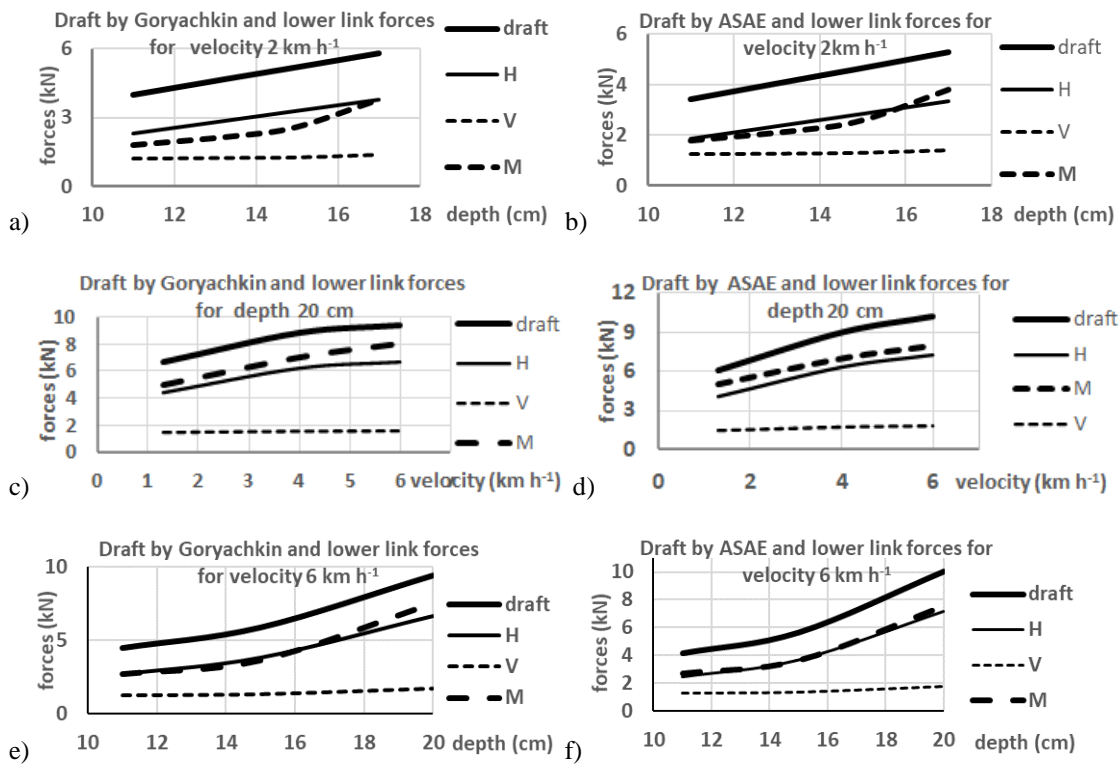


Figure 5- Graphical presentation of average values of calculated forces as dependent on the tillage depth and the tractor speed; a, change of Goryachkin draft, horizontal and vertical forces in lower link and measured forces with depth for tractor velocity 2 km h^{-1} ; b, change of ASAE draft, horizontal and vertical forces in lower link and measured forces with depth for tractor velocity 2 km h^{-1} ; c, change of Goryachkin draft, horizontal and vertical forces in lower link and measured forces with velocity for depth 20 cm; d, change of ASAE draft, horizontal and vertical forces in lower link and measured forces with velocity for depth 20 cm; e, change of Goryachkin draft, horizontal and vertical forces in lower link and measured forces with depth for tractor velocity 6 km h^{-1} ; f, change of ASAE draft, horizontal and vertical forces in lower link and measured forces with depth for tractor velocity 6 km h^{-1}

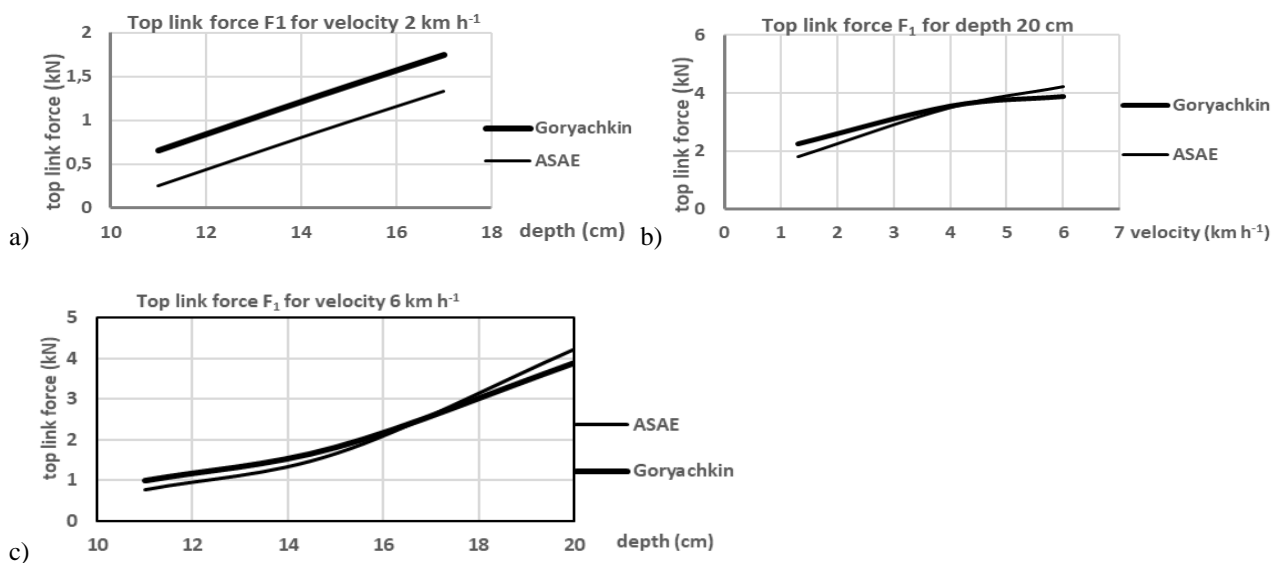


Figure 6- Graphical presentation of average values of calculated forces as dependent on the tillage depth and the tractor speed ; (a), change of top link force with depth for tractor velocity 2 km h^{-1} ; (b), change of top link force with velocity for depth 20 cm; (c), change of top link force with depth for tractor velocity 6 km h^{-1}

4. Conclusions

The presented work discusses the theoretical results of analysis of the forces acting on the links of the three point hitch mechanism. Computer algorithm has been developed for the simulation of these forces. Formulated model comprehends calculation of draft force by two methods (ASAE D497.4 method and Goryachkin method) and, depending on the three point linkage geometry and mouldboard technical characteristics, calculation of forces acting on lower and upper links.

The formulated mechanical model of the THP forces, expressed by equations (3-7) and (9-11) was experimentally verified. The values of the horizontal forces in the lower link obtained by two analytical methods were compared with appropriate experimental values. The application of approximate analytical method of ASAE D497.4 for determination of the draft force resulted in mean signed difference of 0.354 kN as it is presented in Table 3. The Goryachkin's approach of draft force evaluation generated mean signed difference of 0.449 kN. These difference can be reduced by introducing additional experimental data related to the soil properties and the mouldboard geometry in the Goryachkin's algorithm, or to apply some other more advanced method for determination of draft forces. Hence, this paper verifies the applicability of the analytical methods for crude estimation of the forces at the lower and upper links.

Table 3- Difference between measured and the calculated values for the H horizontal component of force acting on lower link hitch point

Measurement	1	2	3	4	5	6	7	8	9	MSD* (kN)
ASAE AD* (kN)	0.84	0.25	0.37	0.56	0.16	0.19	0.01	0.27	0.04	0.3544
Goryachkin AD* (kN)	0.29	0.69	0.85	0.02	0.7	0.73	0.52	0.01	0.23	0.4489

*AD, absolute difference; *MSD, mean signed difference

Results presented in this paper (Figures 5-6) also indicate a general trend of increasing the horizontal forces H and draft forces with plowing depth and tractor velocity. The analogue effects were evidenced with respect to the changes of top link forces F_1 , with plowing depth and tractor velocity, Figure 6. Variations of the vertical lower link forces V were weak.

Abbreviations and Symbols	
$\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$	Link angles
a, T	Ploughing depth, m
A, B, C	Machine parameters
b, W	Width of ploughing tool, m
c_1, c_3	Coordinates of draft application, m
c_2	Coordinate of plough gravity center, m
ε	Coefficient of dynamic resistance, $\text{Ns}^2 \text{m}^{-4}$
f	Friction coefficient
F_i	Parameter of soil texture
F_1, F_2	Top link force and lift link force, N
G	Plough weight, N
H, V	Horizontal and vertical lower link force component, N
k	Specific soil resistance, N m^{-2}
$l_1, l_2, l_3, l_4, l_5, l_6$	Three point linkage geometry, m
l_7	Lower link hitch point distance from the ground, m
n	Number of tools
R	Tractor rear-wheel radius
s, v	Tractor velocity, m s^{-1}

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