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# ANALYSIS OF MEASURED AND COMPUTED FORCE EFFECTS IN TRACTOR'S THREE-POINT LINKAGE DURING TILLAGE

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**Abstract:** *The aim of the paper is an analysis of the measured and calculated force effects which act on tractor during tillage. Effects of the forces on individual driving wheels are analysed too. A mathematical model describing the transformation of force effect acting in the three-point linkage to loads in individual tractor wheels is developed. It is shown that the results of performed computations and theoretical analysis are in a good agreement. Based on the model, it is possible to use the measured force effects for precise determination of forces acting on the wheels. The influence of the length of the upper link on the loading of individual wheels and consequently on the traction performance of the tractor is determined.*

**Keywords:** ***three-point hitch, tillage, force effects, mathematical model.***

## 1. Introduction

The attached or trailed attachments are connected to tractor through three-point linkage, thus force effects acting on tractor are usually significantly different from effects of simple tractive forces, which typically exist in tractive tests. The adhesive loading of driving wheels is generally desirable, since it leads to maximal tractive efficiency. But this action is unfortunately connected with undesirable soil compaction, especially in case of ploughing systems moving in furrow. This fact was documented e.g. in Renius (1981), Upadhyaya et al (1985). Soil compaction can cause serious problems (Nosalewicz & Nosalewicz, 2011) and proper design of working system is thus critical (Cudzik et al, 2010). Adhesive loading of driving wheels is determining factor for achieving the maximal tractive efficiency of tractors. This efficiency consequently highly influences general efficiency of working system. Grečenko (1984) stated that typical difference between tractor performing ploughing and tractor being tested in tractive test is following: the wheeled tractor is moving (by one of its sides) in the furrow and thus it is inclined. In combination with power effects of the plough this inclination causes a different load of individual wheels (moving in the furrow and on the unploughed soil) and changes in the load of both axles. The tractor's tractive properties are thus affected (decreased), especially in the cases when differential lock is not used. This results in significant changes not only in the grip of driving wheels but also in an increased compaction of soil. Design and performance of an adjustable three-point hitch also highly influences the operation efficiency (Al-Jalil et al, 2001). Various data-acquisition systems and different strain gauges systems were used by several authors to evaluate the force effects in the three-point hitch (Al-Janobi, 1984; Al-Janobi, 2000) and/or transmission system (Kim et al, 2000). Also the general models of working tractor were developed (Kolator and Białobrzewski, 2011). The goal of this paper is to develop the precise mathematical model describing the transformation of force effect acting in the three-point linkage to loads in individual tractor wheels. Performed analysis can be used for further studies on dynamic properties of tractor units or other vehicles as described e.g. in Chalupa (2005) and/or Chalupa et al. (2009).

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## 2. Material and experimental methods

Forces measured in the discrete times in the three-point hitch links were selected as an input data: force in the right lift rod, force in the left lift rod, force in the right lower link, force in the left lower link, and force in the upper link (Fig. 2). The load cells measure solely the axial force in the links. It is given by their design and the fact that links are ended by spherical joint on both sides and thus loaded only along the axe. Lower links are the exception, because the sensors are exposed to the bending moment along the axe perpendicular to the plane positioned between lower and lift link. The sensors in the lower links are design in such way that they measure the axial force and do not sense bending. Verification of independence of measured force on the bending of the lower link is a part of experimental verification of calculation. Considering the fact that resulting force acting on the tractor is calculated as a spatial system, it is necessary to determine also the force directives (directions and points of application) altogether with the force magnitudes determined by sensors. Directions and points of application are given by the geometry of the three-point hitch. The forces lie in the lines connecting the joints at the ends of individual links. Thus the geometrical arrangement of the hitch must be determined for each position of the mechanism. The hitch has two degrees of freedom against the tractor: movement of the hitch upwards (change of lifting mechanism links angle, points E-DL-DR see (Fig. 1) and side movement. Both movements are measured by position sensors (potentiometers) and produce the input data for kinematic solution of the mechanism.

Following problems must be solved for determination of forces acting on tractor via three point hitch during tillage:

-mechanism kinematics. The result is a position of the three-point hitch in the space.

-static equilibrium of the forces acting in the spatial mechanism. The result is represented by vectors of force and moment acting on the tractor.

The multi-body software SAMS described in Poreš (1997) was used for creation and solving of the equations. The SAMS software enables both, static and dynamic analysis of the system. Due to large number of input parameters necessary for dynamic model, the static analysis was used to determine the acting forces. The building elements for creation of the mechanism models in SAMS are represented by rigid bodies connected by kinematic joints or constraints. The software works with relative coordinates. The kinematic joints connect the solids in open kinematic chains and enable relative movement of neighbouring elements in the chain. The kinematic constraints close the open chain into closed loop. Topology of the TPH multi-body model and the types of kinematic elements are presented in Fig. 1.

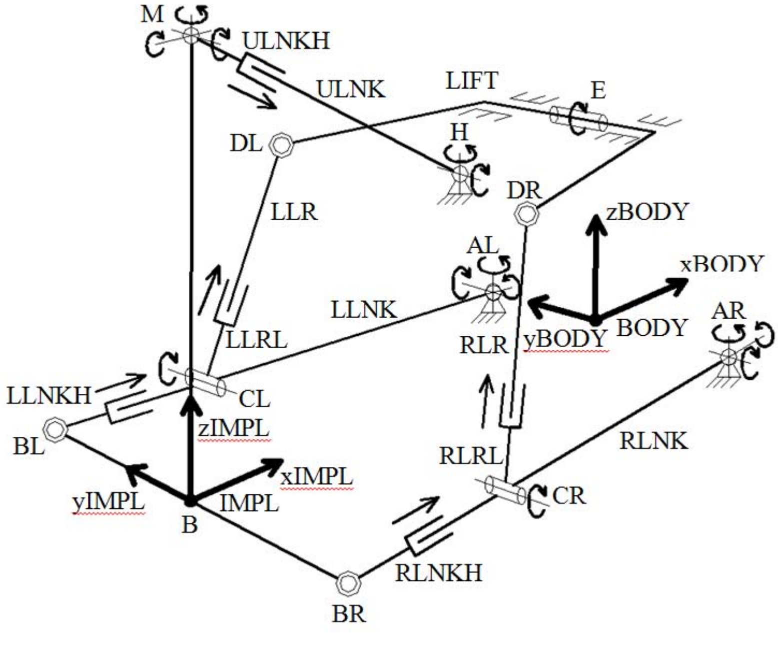

*Fig. 1 Kinematic model of the tractor's three-point hitch*

In order to determine the balance between forces measured in the links and forces acting on three-point hitch mechanism, the links had to be divided into two parts (in the position of sensor location) connected by translational joint enabling the sole reciprocal movement in the direction of the link axe and not enabling any reciprocal rotation. This arrangement allows adding the force element into the model. Both parts would be drawn together by the force equal to the force measured in the strain gauge. Reciprocal relative position of both parts is ensured by constant value of relative coordinate added to the model by translational joint. Each translational joint adds one degree of freedom to the model and corresponding added coordinate is independent value which could be prescribed.

The software SAMS involves the elements, which enable definition of the direction and points of application of the forces or moments of unknown magnitudes. The magnitude of the forces and moments is determined on the basis of dynamic or (as in this case) static equilibrium. These elements determine the unknown magnitudes of force and moment vector components acting on tractor in the origin of system of coordinates „IMPL“ (see Fig.2) and magnitude of moment lifting the hydraulic arms. The number of unknown magnitudes of force effects must be in the case of solving static equilibrium equal to the number of independent coordinates (number of degrees of freedom) in order to find equilibrium for any combination of force effects acting in the direction of any degree of freedom.

TPH mechanism has 7 (originally 2) degrees of freedom after adding of above described translational joints. The number of unknown magnitudes of force elements is also 7. 3 unknown components of force and 3 unknown components of moment acting on the body „IMPL“ (implement) and 1 magnitude of moment lifting the body „LIFT“ (connecting links lifting the mechanism).

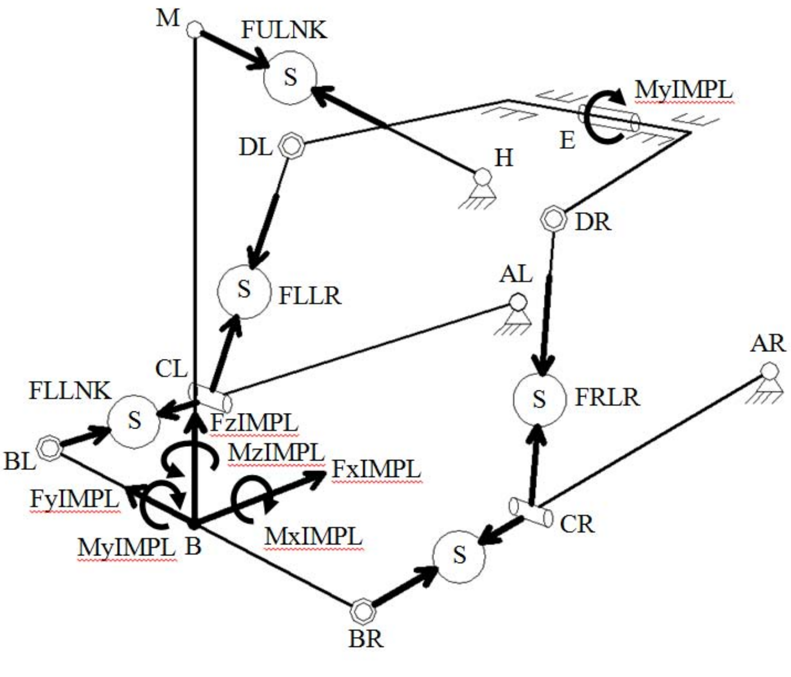

*Fig. 2 Forces, moments and location of sensors (S) in tractor's three point hitch*

The coordinate system „IMPL“ (implement) is an orthogonal right-rotating coordinate system positioned into the middle of the section of a line connecting points BL and BR (connection of lower links to the implement) and it is fixed to the body „IMPL“. The axe $z$ directs from the origin of coordinate system to the point M (connection of upper link to the implement), the axe $y$ lies on the connecting line of the points BR and BL and directs to the left (from the driver's view), and the axe $x$ direct forward (see Fig. 1).

The „BODY“ (see Fig. 3) substitutes the whole tractor in the model, including rear wheels without front axle and wheels and without TPH. This body is connected with auxiliary mass less body "ARM" by spherical joint. The body „ARM“ is connected to the global frame by means of translational joint, enabling translational movement in the direction of its three axes. By this configuration the "BODY" has 6 degrees of freedom. The „BODY“ is also connected in the CFA location with body "FAXL" representing the front axle by the rotational joint. Another degree of freedom is thus added to the set,

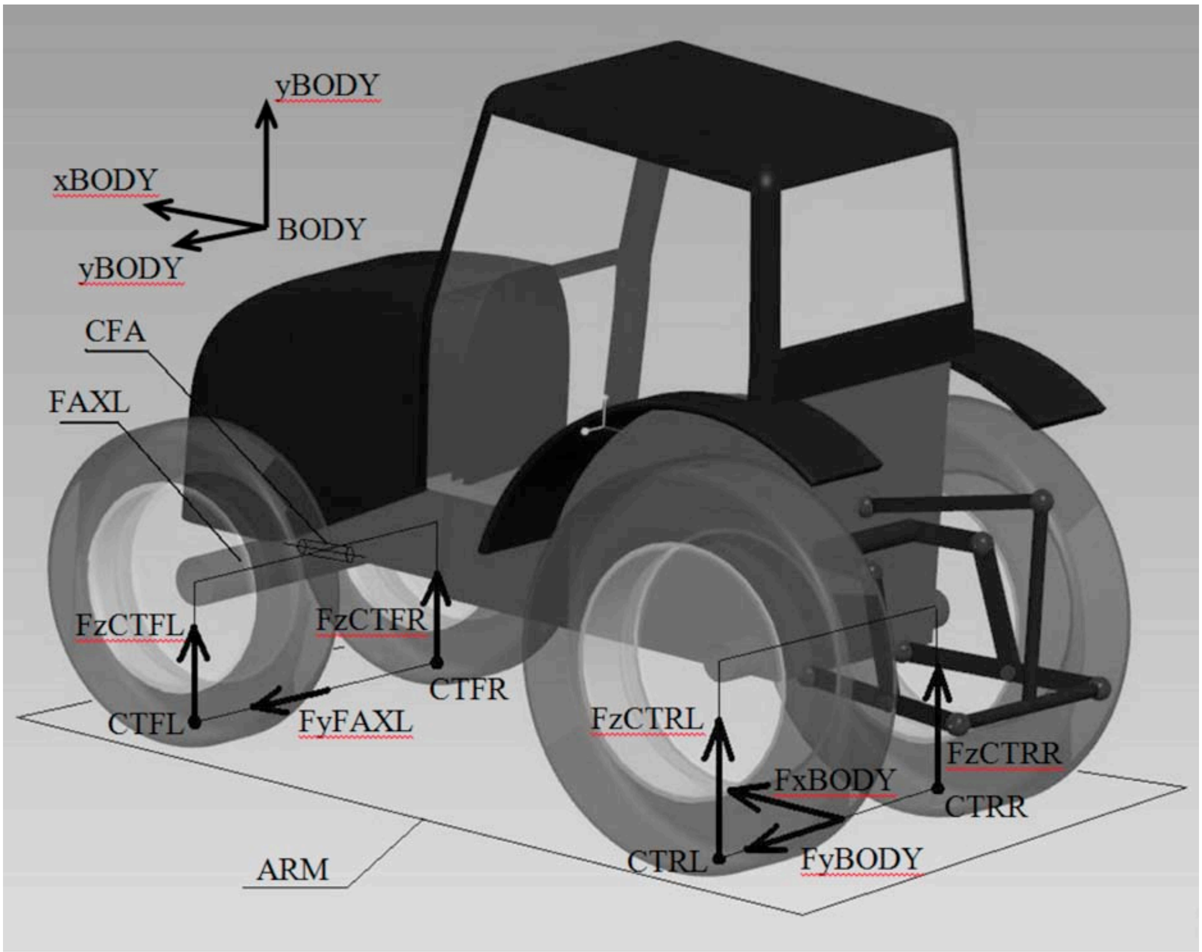

*Fig. 3 Scheme of tractor model*

which means 7 extra degrees of freedom in comparison with model described in the previous part of the text. Following 7 unknown magnitudes of forces and moments can be calculated (see Fig. 3): vertical reaction (wheel loading) FzCTFL, FzCTFR, FzCTRL, FzCTRR in the positions of contact between tyres and ground CTFL, CTFR, CTRL, CTRR; lateral force FyFAXL, resp. FyBODY acting on front, resp. rear axle in the height of ground; longitudinal driving force FxBODY acting in the centre of rear wheel track on rear axle (in the model acting on BODY).

The lateral force acting on front axle FyFAXL represents the sum of lateral forces acting on both front wheels. Its presence in the model is significantly important, because it influences distribution of the total vertical force acting on the front axle between individual wheels of the axle. This simplified model does not allow division of the lateral force acting on the front axle to the forces acting on individual wheels. The same applies for division of lateral force acting on rear axle FyBODY.

The field experiments were performed in the area located close to Slavkov u Brna on the black soil type, loess soil matrix, with the wheat as a pre-crop. The soil was treated by disc harrows (the depth of 8 cm) after the harvest of wheat. The average soil moisture by weight during the experiments was determined as 19.7 %. The ploughing was performed using the tractor Zetor 11741, six-cylinder engine SAME6WTE1, maximal output 78.2 kW at 2000 rpm – measured at PTO by dynamometer Schenk W 400. Maximal torque/revolutions 480 Nm/1400 rpm. Increase of torque: 35 %. Gear box – reverse, mechanical with three-stage torque multiplier. Front tires: 14,9 R 24; rear tires: 18,4 R38. Gross weight of the tractor: 5680 kg; the weight loading the front tire 2920 kg, which represents 51 % of total weight.

The plough Kverneland EM 85, model EM85-200-28, gross weight 1260 kg was used to perform the ploughing operation.

The forces acting in the three-point hitch were monitored using attached strain gauges. The force sensors located on the lift rods – see Fig. 2 (between CL and DL and/or CR and DR) measure solely tensile and/or compression force. The maximal load in tension and compression is 60 kN. The sensors in lower links (between BL and CL; BR and CR) are during normal operation loaded also in bending, except tension and pressure. Their design eliminates these extra loads and solely axial tension loads are sensed. Maximum of 1 % nominal error is guaranteed by producer of the sensors. Schematics of the three-point hitch attached with strain gauges is shown in Fig. 2. The ploughing system was drawn by other tractor and the tractive force FxM in the tow rope was measured by strain gauge sensor Hottinger U2B-100. The maximal load in tension and compression is 100 kN. Uncertainty of measurement for mentioned load cell is 203,4 N, $U_{sensitivity}$ = 26,08 N, $Ut_{empcoeff}$= 26,08 N; $U_{linearity}$ = 200 N.

The testing plot (30 m in length) was indicated on the working area. There was enough space in front of the testing plot to achieve the stabilization of the working system. The forces in the three-point hitch were recorded at 250 Hz frequency and the values were directly transferred to the computer. Average values from 125 force measurements were used in the computational algorithm, which represents approximately 0.9 m of travel. In the total length of 30 m was thus received 34 values for each individual measurement. The forces in the individual links and rods as well as force FxM in the tow rope were recorded in the whole length of testing plot. Altogether, 4 sets of measurement were performed:

Set I: ploughing on the left side, deepness of the ploughing – 17 cm

Set II: ploughing on the right side, deepness of the ploughing – 17.5 cm

Set III: ploughing on the right side, deepness of the ploughing – 25 cm

Set IV: ploughing on the left side, deepness of the ploughing – 27 cm

## 3. Results and discussion

Figure 3 shows the course of computed and measured force FxP as a function of time for Set III measurement. The determined force effects in the three-point hitch and developed algorithm were used for calculation of force FxBODY. The force FxM represents the overall ploughing resistance, which includes plough resistance, rolling resistance and transmission mechanism resistance. The rolling resistance and resistance of rotating parts of transmission mechanism (FxD) were determined experimentally as follows. The plough was lifted into transport position and the complete working system was drawn on the rope. The received values were used for calculation of mean value of FxD. Experimentally determined plough resistance was consequently calculated using following formula:

$$\boldsymbol{FxP = FxM - FxD} \tag{1}$$

Experimentally determined plough resistance FxP was consequently compared with calculated plough resistance, defined using forces measured at three-point hitch and corresponding to theoretical driving force FxBODY. If the calculation of algorithm is correct, following formula must be valid:

$$\boldsymbol{FxP = FxBODY} \tag{2}$$

Received value of FxP force was compared with calculated force FxBODY with use of developed algorithm. Table 1 contains measured values of forces acting in the three-point hitch including plough resistance force FxP. Computed values of forces and their courses during ploughing are as an illustrative case shown in Fig. 2.

The Sets I, II, and IV are not presented, neither in tabular, nor graphical version, due to their large extent, but they are included in the final analysis – see Fig. 4. Listed calculated values represent the force effects acting on the tractor during ploughing. Calculated forces acting on front axle FzCTFL and FzCTFR exhibit negative values, which means that front axle is lightened during working procedure. As it was stated above (in Material and Experimental Methods), the front axle is loaded by 2920 kg, which is the weight sufficient for transmission of driving force from the wheels to the ground. It is evident from calculated values of FzCTRL and FzCTRR forces, that ploughing operation increase the load of both rear wheels. The calculated forces acting in the transverse direction in the $y$ axis reach relatively low values with reference to adhesive forces (forces in $z$ axis) and thus can not produce instability of the working system in transverse direction.

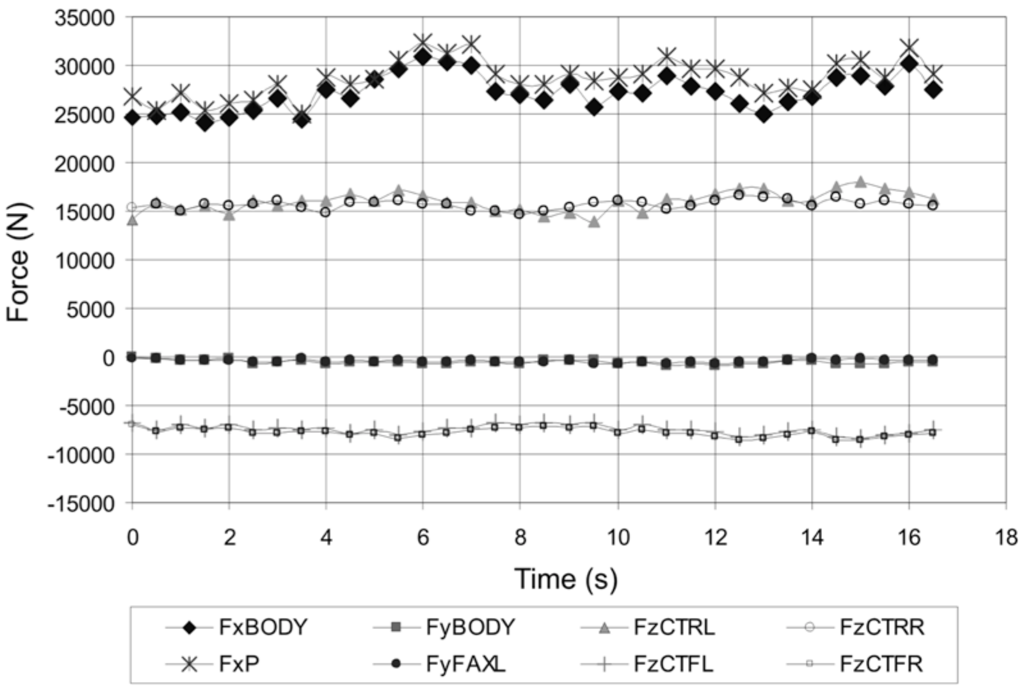

*Fig. 3: Measured course of the force FxP and computed forces acting on ploughing tractor as a function of time – SET III*

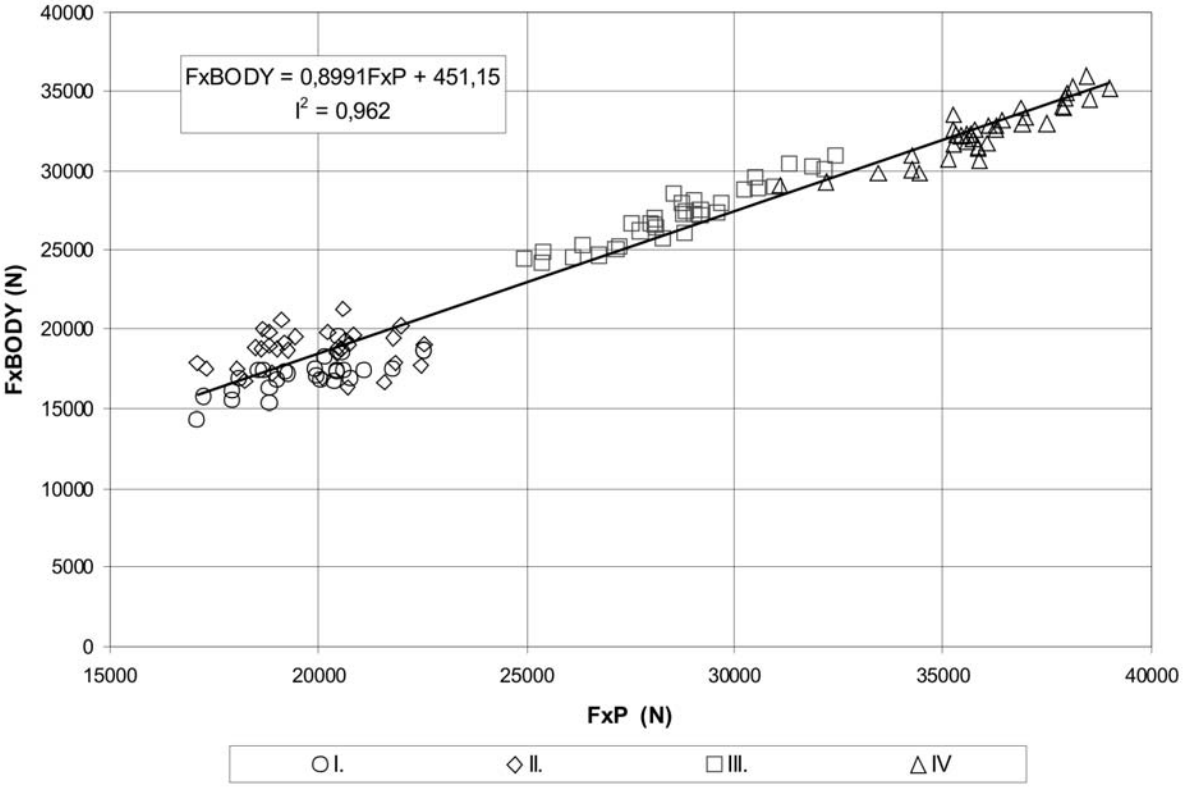

*Fig. 4: Dependence of theoretically calculated plough resistance FxBODY on experimentally determined resistance FxP. I., II., III., and IV. denote measuring sets.*

Ideally, the courses of FxBODY and FxP should overlap each other – see Fig. 3. The variations and differences are probably caused by inexact determination of rolling resistance and resistance of rotating parts in the transmission mechanism. The resistance forces were determined for ploughing system with plough in the transport position. The tractor's tires were loaded solely by weight of the machine (tractor) and the plough. But it is important to note, that forces acting on ploughing tractor are given by sum of plough weight and resistance forces acting on ploughing elements. The vertical components of ploughing elements resistance forces produce more intensive loads on tractor tires and thus increase the overall rolling resistance. This explanation is supported by the fact that experimentally determined plough resistance is bigger than calculated one. The verification of the mathematical model was performed by use of regression test, which involved dependence of theoretically determined plough resistance FxBODY on experimentally determined plough resistance FxP – see Fig. 4.

As it is obvious from regression analysis shown in Fig. 4, the measuring sets I and II are characterized by larger variation of calculated and measured values in comparison with sets III and IV, which exhibit smaller level of data scatter. This result can be explained as a consequence of a fact that measuring sets I and II were connected with 17 cm working depth of ploughing, while sets III and IV with 27 cm depth. The forces in case of sets I and II were thus lower indeed. This difference also produced larger exposure of the forces, which were not possible to measure chronologically together with other monitored force effects. This is especially the case of rolling resistance and/or forces of rotating parts of transmission mechanism, where larger variation of measured and calculated values was found. Presented results are in general accordance with conclusions presented by Bauer and Sedlák (2003).

Performed statistical analysis proven that calculated value of theoretical plough resistance FxBODY and experimentally determined value of plough resistance FxP clearly exhibit the linear dependence. The high value of determination coefficient approves the high dependence tightness. It can be concluded from the determination coefficient value $I^2 = 0.962$ that 96.2 % of calculated values variability is defined by proposed regression function. The results of regression analysis are listed in Table 3 and Table 4. The regression function was tested by F-test and the result of the test is included in Table 3. It is obvious that tested regression function very well describes the measured values. The performed t-test (and the results listed in Table 4) revealed that coefficient significance, where the coefficient represents the slope of the line) is very high. Test of the absolute term of equation approves its low significance.

*Tab. 3: The test of regression function*

| | Difference | SS | MS | *F* | Significance F |
|---|---|---|---|---|---|
| Regresssion | 1 | 5.2E+09 | 5.2E+09 | 3216.36 | 4.61E-92 |
| Residua | 127 | 2.05E+08 | 1615405 | | |
| Sum | 128 | 5.4E+09 | | | |

*Tab. 4: The test regression coefficients*

| | Coefficients | Error of the mean value | *t-stat* | *P* value |
|---|---|---|---|---|
| Limits | 451.1531 | 439.2477 | 1.027104 | 0.306324 |
| FxP (N) | 0.899093 | 0.015853 | 56.71296 | 4.61E-92 |

## 4. Conclusions

The presented results and performed analysis approve that theoretically calculated plough resistance correspond to experimentally determined values. Thus it is possible to conclude that mathematical model is functional with satisfying level of accuracy and measured force values in the three-point hitch can be used for calculation of force effects arising during ploughing operation on individual tractor wheels. If the force effects on individual wheels (with attachment connected to the three-point hitch) are known, it is possible to formulate and determine the traction characteristics. It is e.g. possible to evaluate, how different types of attachment connection influence the load of individual wheels. The change and alternation of the force effecting in the upper link of the three-point hitch, which can be influenced and determined by adjustable length, highly influences the final load of tractor's axes. It was experimentally determined and confirmed by consequent calculation with use of proposed algorithm, how exactly the length of the upper link influences the loading of individual wheels and thus traction performance of the tractor. The further research will be focused on detailed analysis of the different types of plough connection and its influence on loading of tractor's wheels, when considering weight of the machine, its inclination, and kinematics of the system.

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