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New method for monitoring tire-soil individual stresses

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Kurzfassung

Neue Methoden für das Monitoring von spezifischen Bodenbelastungen

Die Vermeidung oder Verminderung anthropogen verursachter Beeinträchtigungen der Bodenfunktionen gehören zu den Leitbildern einer nachhaltigen Landbewirtschaftung. Das allgemeine Interesse an der Vorsorge und Abwehr von Gefahren durch nachhaltige Schäden am Boden wurde mit der Verabschiedung des deutschen Bundes-Bodenschutzgesetzes 1998 festgeschrieben.

Im physikalischen Bodenschutz spielt das Problem der Bodenverdichtung eine bedeutende Rolle. Die Einhaltung von Grundsätzen zur guten fachlichen Praxis hilft schädlichen Bodenverdichtungen vorzubeugen. Die technischen Möglichkeiten und Arbeitsverfahren für bodenschonendes Befahren werden ständig weiter entwickelt. Zusätzliche Informationen durch Sensorsysteme, die eine Online-Bewertung von Bodenbelastung und Bodenreaktion liefern, können die Effektivität des Bodenschutzes weiter erhöhen. Arbeiten an einem Online-Befahrbarkeitssensor werden in dieser Arbeit vorgestellt.

Schlüsselwörter: Bodenverdichtung, Reifen-Boden Interaktion, Spannungs-Monitoring, Befahrbarkeit

Abstract

Among the recurring problems in agriculture are the avoidance or reduction of anthropologically caused disturbances on soil functions. It is in common interest, since the adoption of the German Soil Protection act in 1998, that while farming, precautions and a reduction of damaging practices are to be taken into consideration.

In the area of physical soil protection, the problem of soil damaging compaction is one of the most essential. Measures to protect the soil through “best management practices” have been analysed. All those measures are challenged to further develop these practices as well as innovative techniques. Within the range of innovative techniques, the monitoring system development of tire-soil individual stresses may have great significance for sustainable agriculture. The prototypes of such system are currently being studied in field tests. The main objective of this research is development of an on-line traffickability sensor for high performance agricultural machinery.

Keywords: Soil compaction, tire-soil interaction, individual stress, monitoring, trafficability

1 Introduction

Soil damaging compaction is used to describe the soil compaction, which through its soil structural changes, causes permanent negative effects on the soil functions (yield, regulation and habitat functions). It can take place in the topsoil, in the base of the topsoil and in the subsoil. That is why it is necessary to keep the soil stresses caused by driving over land at such a level that it does not lead to soil damaging compacttion. For this purpose, the technical processing and crop farming possibilities offered by best practice management, which address the location, farm and crop sequence of a specific farm (BMVEL, 2001) with a particular view to the subsoil, are not adequate at the moment.

Indicator concepts and sensor systems can contribute to characterising the mechanical soil load and the soil bearing capacity and to creating decision-making helps for soil-conserving passage on cropland. The application of microprocessor technique and use of adequate models of tire-soil interaction process may

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stimulate the development of an on-line trafficability sensor system. Trafficability is understood as the mechanical soil bearing capacity tolerance of soil without negatively affecting the soil functions.

2 Methods

2.1 Indicators for the problem of soil damaging compaction

Precautions, danger prevention and rectification are the three legally required protection steps against damaging soil changes. For dividing between these steps, test values are needed, that are based on significant soil compaction indicators (Table 1).

Table 1.
Indicators regarding the problem of soil compaction

vehicle load	soil stresses	soil bearing capacity	soil structure
– wheel load – contact area pressure – tyre inflation pressure	– models based on contact area pressure and depth functions	– pre-compression load – shear strength – soil moisture	– air capacity – soil density – water conductivity – rootability

The soil structure parameters are used to recognize soil damaging compaction as well as to monitor the success of protection measures. The bearing capacity is used to get knowledge about the soils reaction to loading. If the soil is stressed higher than the bearing capacity, strain and compaction may be the consequence. Soil bearing capacity is mainly influenced by soil mechanical properties and soil moisture.

The contact area pressure p_k, is the common input value for soil stress models. It is usually used as the mean value of the wheel load and driving force divided by the contact area of the tire/soil. It is also influenced by the tyre inflation pressure. It determines the initial stress near the soil surface during travelling. The real contact area pressure is comprised of normal (as a consequence of vertical stress) and shear stress (as a consequence of the horizontal stress through driving force and breaking power). Thus, due to the various divisions within the contact area and particularly due to the unknown real contact area, the use of the average contact area pressure as an indicator for in-situ decisions is problematic. Nevertheless, the contact area pressure is essential for modelling soil stresses in deeper soil layers using models according to Söhne (1958).

In this studies, a new method is tested to improve the determination of real contact area pressure by using the model from Jaklinski (1999) that calculates normal and shear stress within the contact area as influenced by the wheel load, tyre inflation pressure, contact area and tyre deformation.

2.2 Model of pneumatic wheel acting on soil

Soil as a variable medium (with regard to composition, state, and moisture) can be characterized by variable traction parameters *c* and ϕ, as well as variable deformability.

Up to now the used methods for the estimation of soil compaction degree and a value of bearing individual stresses, are relaying on average values with reference to the total considered cultivable land area. Such approach does not take into account the possibilities of occurrence of places where there is considerable concentration of components of stress state, which cause the exceeding of limit stress values and soil deformation.

The models, which have been applied so far (Becker, 1956; Janosi and Hanamoto, 1962; Wanjii et al., 1997), usually describing distribution of tangent components of individual soil-tire stresses, treat soil and the traction mechanism as separate objects. For that reason it is necessary to determine each time soil parameters c (cohesion) and ϕ (angle of internal friction) at its changing humidity. It is a real limitation of research tests in the field conditions.

However, presented in work equations treat the soil and traction mechanism as one object in which their mutual interactions are intermingled. Due to their interaction, there is a variable value of the tire penetration depth z and the tire deflection e during the tire passing. The tire penetration and its deflection will be changing as the result of the soil condition, its humidity and its mechanics.

The proposed method is based on Jaklinski equations describing the values of the normal and tangent components of individual stresses in the function of angles (α_o, β_o, γ_o) describing the tire-soil contact surface (see Fig. 1).

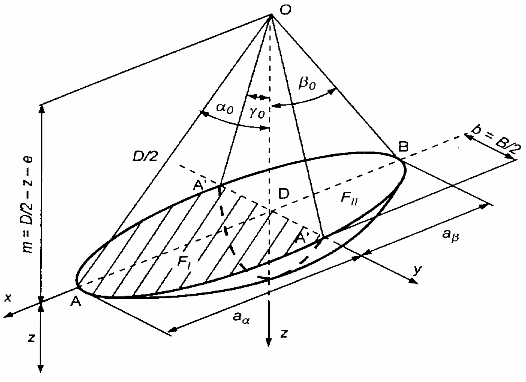

Figure 1
Space of distributing the external load on the elliptical tire impressed area on the soil

The shape of the area of the tire-soil interaction F_c was accepted as an elliptical one. As it results from the research tests conducted by Jaklinski, this shape is approximate to the real one.

The normal (σ) and shear (τ) components of individual stresses caused by pneumatic wheeled running mechanism can be obtained from the following relationships below presented (Jaklinski, 1999):

$$\sigma(\alpha)=\frac{\int_{o}^{\alpha_o-\alpha}\sqrt{P_u^2+\frac{G^2}{(k_1\sin\alpha+\cos\alpha)^2}-2\cdot P_u\cdot\frac{G\cdot\sin\alpha}{k_1\sin\alpha+\cos\alpha}}d\alpha}{k_2\cdot[\mathrm{tg}(\alpha_o-\alpha)+\mathrm{tg}(\beta_o-\beta)]\mathrm{tg}(\gamma_o-\gamma)\cos\left(\frac{\pi}{2}-\phi\right)}$$

$$\tau(\alpha)=\frac{\int_{0}^{\alpha_o-\alpha}\sqrt{P_u^2+\frac{G^2}{(k_1\sin\alpha+\cos\alpha)^2}+2\cdot P_u\cdot\frac{G\cdot\sin\alpha}{k_1\sin\alpha+\cos\alpha}}d\alpha}{k_2\cdot[\mathrm{tg}(\alpha_o-\alpha)+\mathrm{tg}(\beta_o-\beta)]\mathrm{tg}(\gamma_o-\gamma)\sin\left(\frac{\pi}{2}-\phi\right)}$$

where:

P_u – pulling force,
G - vertical load,
α_o, β_o, γ_o - angles describing the tire-soil contact surface,
α, β, γ - angles of soil-tire interaction from the ranges of $0\le\alpha\le\alpha_o$; $0\le\beta\le\beta_0$; $0\le\gamma\le\gamma_0$,
k_1, k_2 - coefficients characterizing constructional and operational parameters of a driving vehicle and representing soil parameters:

$$k_1=\frac{D-2\cdot e}{2\sqrt{D\cdot e-e^2}};\quad k_2=\left(\frac{D}{2}-z_o-e\right)^2\frac{\pi}{2}\ [\mathrm{m}^2],$$

where:

D - tire diameter,
e - tire deflection on soil.
z_o – tire caving into soil (maximum depth rut).

Pulling force P_u, occurring in equations above mentioned can be measured and registered in the function of variable slip s, and then approximated with the earlier assumed function (e.g. the function genfit – MathCAD 6.0Plus) continuously during the whole measuring cycle.

The tire-soil interaction angles α_o, β_o, γ_o can also be measured and registered continuously by means of sensors measuring directly values of the above-mentioned angles or by means of measurement of the length of sections which stand for elliptical axes of tire impression shape on soil a_α, a_β, b.

The coefficients k_1, k_2, characterizing tire-soil interaction consider both variables soil conditions during the measuring cycle and changeable soil conditions, can be calculated continuously from adequate equations.

For the further considerations of tire-soil interaction, the coordinated system (in Fig. 2) has been admitted to determine the contact area and the tire deformation.

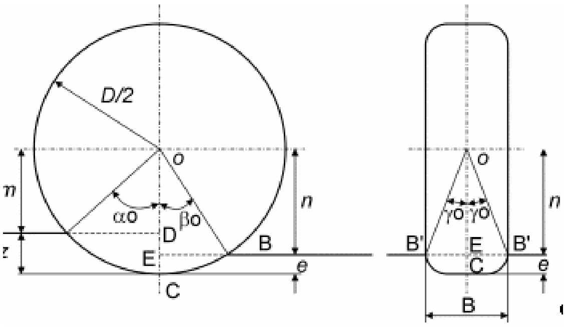

Figure 2
Parameters of Jaklinski model to determine the contact area and the tire deformation

Variable parameters of tire-soil interaction under field conditions will be shown during tire pass by means of continuous registering the wheel track z and variable tire deflection on soil e, with assumed research parameters. Parameters of tire impressions and deflections will be changing continuously not only together with subsoil structure change but also with its humidity

2.3 Development of a model supported sensor system

For the implementation of machinery, the development of sensor systems is well suited to support short term decisions for soil conserving passage. The first prototype of a laser sensor is based on the indicator track depth for a classic evaluation of the trafficability through the farmer, which does not suffice as an integrated parameter for all factors affecting the traffic, particularly for subsoil protection. That is why for the complex problem of subsoil damaging compaction, further technical approaches are included: among others a model supported sensor project to evaluate the actual contact area pressure currently being studied in field tests (Jaklinski et al., 2001).

The practical application of the Jaklinski model for individual stresses testing requires the developing of method for continuous measurement of two angles α_o and β_o.. The measuring of angle γ_o is not necessary during test because tire deflections in plane perpendicular to its axis are small and they have not significant influence on calculated value of the soil-tire interaction area. The angle γ_o can be simply calculated on the ground of tire constructional parameters (D, B).

The newest idea to determine the individual tire-soil stresses is the testing of inflation pressure change. It is known that inflation pressure change p_o is conditioned by tire deformation, which is dependent on firmness of soil and its parameters, and soil-tire interaction area. The model for the circumscribing of pressure change-stress values is not available. Hence a development of new model on the base of results from field test experiments and use of statistical analysis has been determined to develop.

2.4 Microprocessor monitoring systems

For determination of state stress components the method of real time measurement of angles α_o and β_o has been developed at the Institute of Mechanical Engineering of Warsaw University of Technology (Plock, Poland). The method was implemented towards two versions of microprocessor monitoring system.

The first version of microprocessor monitoring system consists of two mating parts (stationary and rotated) coupled by shaft. For transfer of measuring signals between these parts the optical-electronic link is designed. The block diagram of the system is shown in Fig. 3.

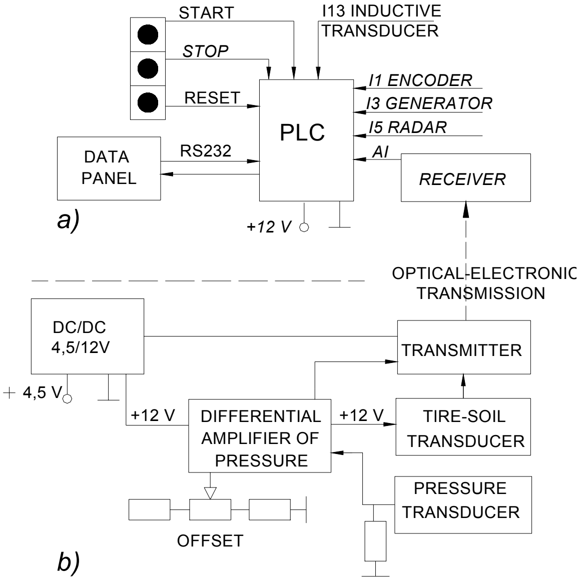

Figure 3
Block diagram of the first version of system: a) stationary part, b) rotated part

The view of the monitoring system is shown in Fig. 4. The body of stationary part carried the following sets:
- PLC controller,
- data panel,
- pulse generator,
- encoder,
- inductive sensor.

The mounting plate of movable part has been driven by single wheel of tested vehicle (FAL). This part was equipped with the following main sets:
- DC voltage converter 4,5/12 V,
- tire-soil contact transducer,
- pressure transducer with reference set,
- optical-electronic transmitter.

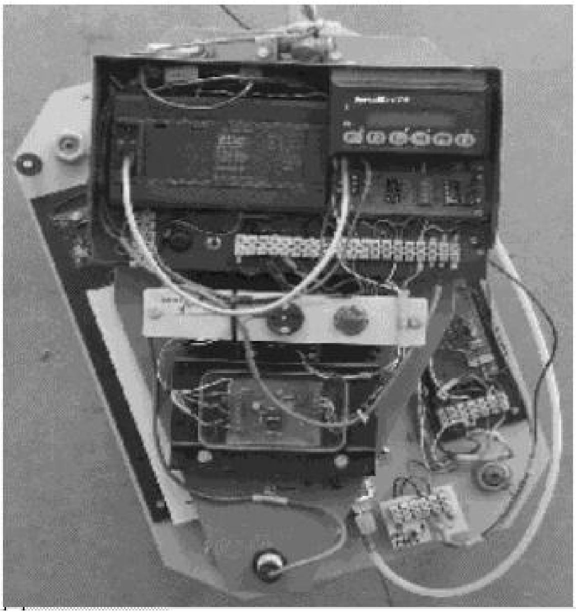

Figure 4
The view of the first version of monitoring system

The principle of operation of tire-soil contact transducer consists in retuning of oscillator by capacitance of set: electrode at tire tread-soil. If the electrode approaches soil the capacity will increase and consequently the frequency is decreased. Then the frequency signal is converted into voltage one (by f/U converter). Exceeding a threshold value of voltage is treated as a tire-soil contact occurring.

The measurement of inflation pressure change is done by transducer type PC-50. The range of pressure change caused by change of stresses is relatively small (max 0.5 %), hence the differential method of measurement has to be applied. The signal from pressure transducer is compared with reference signal (offset), and the difference value is amplified.

The PLC controller (VersaMax Micro 23) is designated for automatic control of measuring process, signal processing and data logging. The data panel (Datapanel 45) is available for the reading-out of data. The simplified algorithm of measurement process control is shown in Fig. 5.

The presented algorithm and functioning program provide evaluation, for 10 turns of wheel, the following quantities:
- slip of tested wheel,
- angles: αo and βo,
- - depth rut z,
- change of tire inflation pressure.

The slip of tested wheel has been evaluated on the basis of measurements of travelling speed of tested vehicle (radar) and rotational speed of wheel (encoder). In the measuring of angles the impulse generator and block of high speed counter (HCS) of PLC.

For the detecting of vertical position of tire-soil contact electrode the inductive transducer is used. The depth rut is calculated on the basis of wheel dimensions and values of angles α_o and β_o.

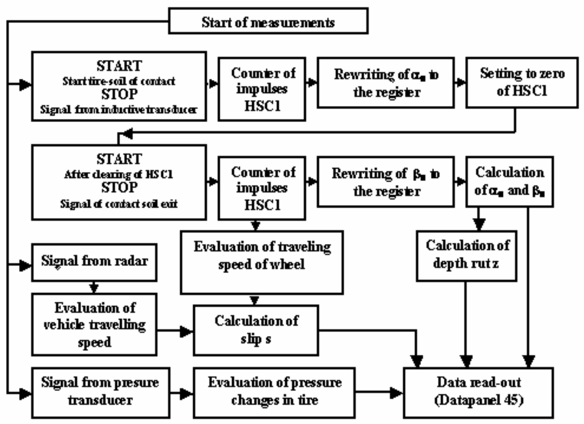

Figure 5
Algorithm of measurement process control

The second version of the microprocessor monitoring system has been developed towards simplification of mechanical construction and the increasing of functional capabilities. Two parts of system are not mated mechanically. It has been achieved by application of 4-channel radio transmission of signals (433.92 MHz, AM). The view of this system is shown in Fig. 6.

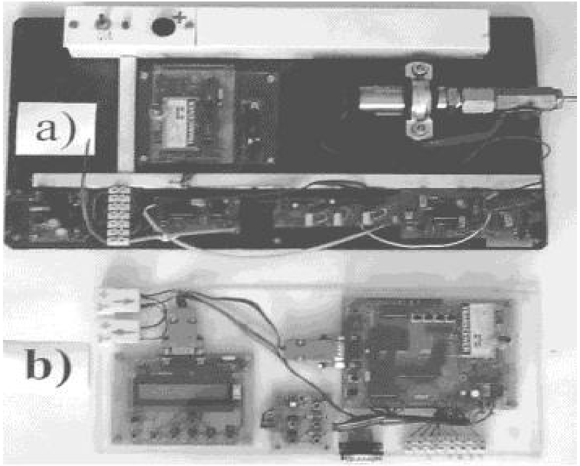

Figure 6
The view of the second version of the microprocessor monitoring system: a) rotated part, b) stationary part

The stationary part of a system is equipped with radio receiver and data collecting block. The data can be transferred to PC computer and processed by Excel program. The visualisation of courses of measured signals during the test is also possible.

3 Field tests

The field verification test has been carried out at FAL Braunschweig in 2002 (Jaklinski et al., 2002, Sommer et al., 2003,). The view of first monitoring system in co-operation with FAL tested vehicle during the field tests at FAL is shown in Fig. 8. For the test has been used the Michelin 20.8R38xH108 (D = 1.81 m, B = 0.549 m).

According to the model Jaklinski (1999) a system makes possible the calculation of normal and shear stresses within the contact area from the parameters α_o, β_o, γ_o and e of the tire deformation (Fig. 7) as well as the indicators wheel load, driving force and slip.

Figure 7
The view of the wheel equipped with the first monitoring system during field tests

Table 2
Normal and shear stresses in the contact area below the wheel centre depending on the deformation criteria according to Figure 1 and the parameter driving force, wheel load and slip as mean values for 10 wheel rotations.

Wheel load [kN]	39				55	
Inflation ressure [kPa]	200		250		250	
Slip (%)	10	20	10	20	10	15
Pulling force [kN]	14.9	17.4	14.0	16.8	18.1	20.3
Normal stresses [kPa]	162	144	172	150	238	224
Shear stresses [kPa]	59	62	59	62	76	81

It is known that with increasing wheel load in the case of constant inflation pressure, the contact area pressure increases, and by constant wheel load with decreasing inflation pressure, the normal stress on the contact area reduces. This is reflected in the measurement with the single wheel measurement equipment and the calculations according the Jaklinski model (see Table 2).

4 Conclusions

Agriculture needs high performance machinery and equipment. A consequence of appropriate technology are the wheel and vehicle loads which, in contrast to mechanical stress previously experienced, has a greater and deeper impact on the soil structure.

Today’s wheel loads (Sommer et al., 2001) really do provide a cause for concern that the soil damaging compaction exists or can occur as a consequence of traffic under wet soil conditions. This can have a permanent negative influence on soil functions.

A further development of a traffickability sensor may improve the knowledge about the soil compressive forces in situ and may help to find a most effective practice management for soil protection against compaction.

References

Bekker M-G (1956): Theory of Land Locomotion: The University of Michigan Press, Ann Arbor

Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft (BMVEL) (2001): Gute fachliche Praxis zur Vorsorge gegen Bodenschad-verdichtungen und Bodenerosion, Bonn (2001): 105 p

Janosi Z, Hanamoto B (1962): Analytical determination of drawbar pull as a function of slip for tracked vehicles in deformable soils: Mechanics of Soil-Vehicle Systems: Edizoni Minerva Technica, Torino

Jakliński L (1999): Modele oddziaływania koła pneumatycznego na glebę (habil.-thesis): Prace Naukowe, Mechanika, z. 175, 116 pp, ISSN 0137-2335

Jaklinski L, Jasinski B, Sommer C, Lebert M (2001): The field test verification of new mathematical model for the calculation of individual soil-tire stresses: Proceedings of the IV International Conference "Microprocessor Systems in Agriculture": PW Plock, pp 62 – 67, ISBN 83-908324-8-8

Söhne W (1958): Fundamentals of pressure distribution and soil compaction under tractor tyres: Agric. Eng. 39: 272-281, 290

Sommer C, Walter K, Lebert M, Jaklinski L, Jasinski B (2001): Effiziente und bodenschonende Triebkraftübertragung vom Reifen zum Boden: 56 Landtechnik 5: 316-317

Sommer C, Lebert M, Jaklinski L, Jasinski B (2003): Bodenschadverdichtung – Strategien und Techniken zum physikalishen Bodenschutz: 58 Landtechnik 2: 94-95

Jasinski B et al. (2002): Report on the field test verification of the new method for tire-soil individual stresses monitoring, Federal Republic of Germany/Poland, project no 126: Typescript, 70 p

Wanjii S et al. (1997): Prediction of wheel performance by analysis of normal and tangential stress distributions under the wheel-soil interface: J. of Terramech.:, Vol. 34, No. 3, pp 165-186