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Integrated wheel load measurement for tractors

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Soil protection, increased traction performance and optimized fuel consumption are the main drivers in tractor development today. A minimum axle load leads to maximal soil protection, whereas a certain weight is necessary to achieve the requested traction force. Therefore, large contact areas should transfer the axle loads to the soil. On the one hand, there is the need to distribute the tractor weight proportional to the ratio of tire sizes to the driven axles. On the other hand, the tire inflation pressure should be set to the smallest allowed value for soil protection, restricted by the overload capacity of the tire. A measurement approach is presented below which allows the determination of vehicle wheel and axle loads during the work process. For rigid rear axles, the body structures integrate the required sensor system, for hydropneumatically suspended axles, pressures of the hydraulic cylinders are analysed. The identified axle loads can be displayed to the operator and used for additional assistant systems for tractor optimization.

Keywords
Axle load determination, sensor system, soil protection, magnetostriction

To increase efficiency of agricultural process chains, farmers use larger and especially wider implements, which demand an increased traction potential of tractors. This carries the trend of increasing installed engine power in tractors and agricultural machinery (Renius and Knechtges 2009, Herlitzius et al. 2013), which also causes an increase in vehicle masses. Although the predominant use of all-wheel drive could reduce the power-to-weight ratio, only a corresponding machine mass can transmit engine power into effective tractive effort. The strength of the agricultural soil limits this evolution, especially of rising vehicle masses. In terms of its composition and structure, the soil has a decisive influence on the crop yield. Driving on agricultural fields leads to soil compaction and rearrangement of the soil structure beneath the tire.

So called pressure bulbs describe soil stresses. These illustrate as isobars the pressure distribution in the soil (ground pressure). Both, the contact area beneath the tire and the tire load can influence the pressure level. Figure 1 shows pressure bulbs in a secondary podsol as an example for a "Multibib" tire of the dimension 650/65 R38 by the company Michelin for dry conditions. Increasing wheel loads and rising tire inflation pressures, which reduce the footprint of the tire, affects vertical stresses in deeper soil layers and the risk of harmful soil compaction increases.

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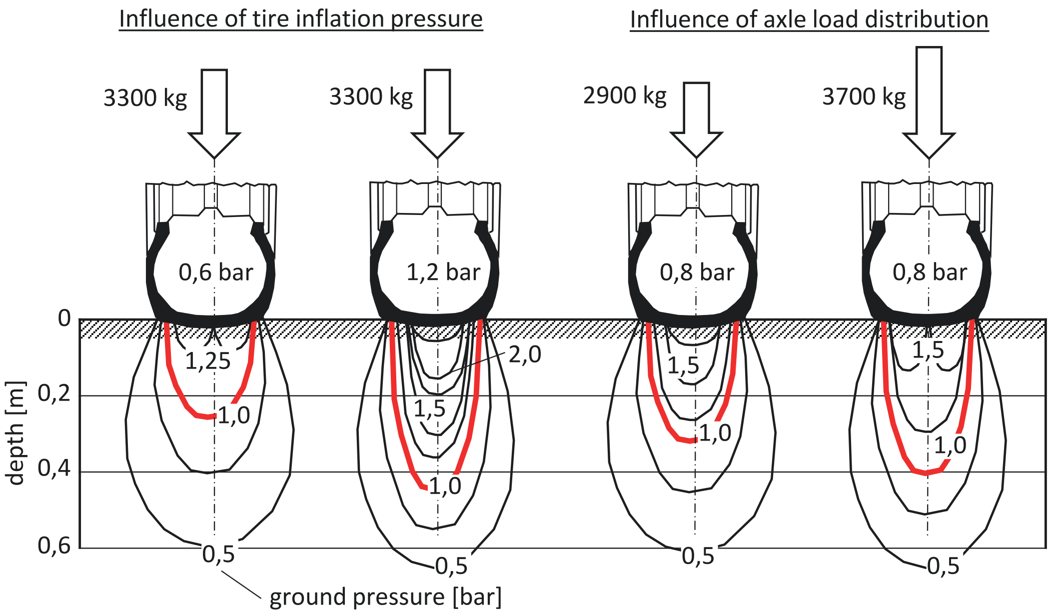

Figure 1: Pressure bulbs beneath a tire Michelin Multibib 650/65R38 on dry secondary podsol (CH7) for various tire loads (left) and various contact area (right), calculated with the soil-compaction-model Terranimo (Stettler et al. 2014)

Soil compaction occurs, when the soil pressure exceeds the soil resistance (soil stability). The comparison of these two parameters for soil layers in the subsoil (beneath a depth of approx. 30 cm) is particularly crucial, because compaction at this depth is irreversible in terms of today's standardized tillage measures such as cultivating or plowing. The soil pressure in the topsoil is mainly caused by the contact area and thus the tire inflation pressure, the soil pressure in the subsoil is significantly influenced by the vertical wheel load (Stettler et al. 2014).

Both, the tire inflation pressure and the vertical wheel load are adjustable values by the tractor user, at least within limits. The tire load bearing capacity, which describes the relationship between the permissible vertical wheel force and the minimal tire inflation pressure for each individual tire size, links the values to one another. In order to preserve the largest footprint at a given vertical tire load in terms of soil protection, it is recommended to reduce the tire inflation pressure to the minimal permissible value (BMVEL 2002; VDI 2014). For a multi-axle vehicle with all-wheel-drive the vehicle mass needs to be distributed on all axles to use the mass efficiently for tractive effort. The axle load distribution can be adjusted in a first approximation according to the ratio of the projected tire contact area (diameter * width) to achieve the same minimal tire inflation pressure on all axles.

The example of a common tire combination, 650/65R38 rear and 540/65R28 front, for a mid-range standard tractor (140 kW) points out the sensitive dependence on axle load distribution and minimum tire inflation pressure. Figure 2 shows the permissible axle loads for the necessary tire pressure for tires of the Michelin Multibib series (MICHELIN) when used in a heavy pulling operation (7 km/h). In order to be able to transfer the installed engine power into tractive power, a vehicle mass of 11,000 kg is determined. The ratio of the projected tire contact area of the mentioned tire combination results in an ideal percentage axle load distribution of front/rear = 39%/61%. For three different percentage axle load distributions (front/rear = 50%/50%, 40%/60%, 30%/70%), the resulting axle loads and related minimal tire inflation pressures are shown. Almost optimal ballasting situation of 40%/60% allows the same minimal tire inflation pressure of approximately 0.9 bar on both axles. When leaving the recommended ballast range, the tire inflation pressure of one axle increases significantly while the other axle is unloaded to such an extent that the theoretical tire inflation pressure falls to the limit or even below the minimum permissible tire inflation pressure. In order to operate the tire to full capacity, which means to set the inflation pressure to minimum permissible value, the actually acting vertical tire force needs to be known.

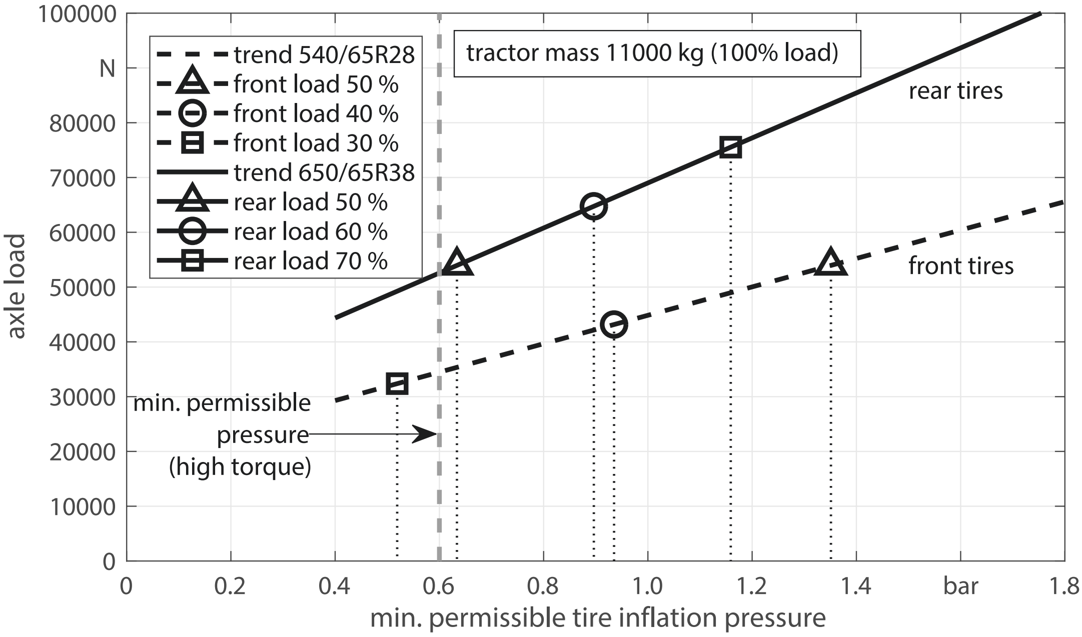

Figure 2: Axle loads (addition of 2 tires) and appropriate minimal tire inflation pressure for various axle load distributions for a middle range standard tractor equipped with Michelin Multibib tires

Today operators use stationary tire or axle load weighing systems to determine axle loads. However, the axle loads determined in standstill change in the working process due to vertical and horizontal forces transferred from the implement to the tractor. Horizontal forces change the axle load distribution whereas vertical forces increase the effective vehicle mass. Furthermore, inclinations in longitudinal and lateral direction of the vehicle influences the dynamic wheel loads. Continuously measurement of dynamic vertical tire forces requires a measuring system integrated into the tractor body (Pichlmaier 2012, Wieckhorst et al. 2015). Strategies for vehicle ballasting and settings for tire inflation pressures are derived from the real-time measurement data during the working process in order to achieve the sweet spot for soil protection and ensuring overload protection for the tires at once.

State of the art and system analysis

Vertical tire forces can be calculated when knowing the machine‘s center of gravity and the acting forces from ballasting and implements via equilibrium equations. Due to the variability of force application points of a tractor, to connect implements or ballasting weights, this method would require a corresponding number of measuring points for recording the several forces. The contact areas of the tires or drives on the ground carry all forces acting on the tractor. Therefore, the most sensible measurement points for the detection of vertical tire forces and determination of the related vehicle mass and axle load distribution are on the axle body or axle shaft. Such measurement points are preferred within the meaning of a reduced number of necessary sensors. In the field of agricultural and construction machinery, the determination of vertical wheel forces has been particularly focused over the last 10 years. There are already several integrated measuring systems known from patents and existing applications. However, the use of such a measurement setup is not known for serial production tractors.

For suspended axles several systems are used which detect the load condition of the hydraulic, pneumatic or hydropneumatic suspension system. Pressures on the piston- and ring-side of the suspension cylinder are measured and calculated via cross-sectional areas into forces. In DE 10029332 B4 (Continental AG 2000) such a system is described for pneumatic axle suspensions for commercial vehicles and trailers. Pichlmaier (2012) and DE 102015206369 A1 (Deere & Company 2015) show the axle load measurement for hydropneumatic suspended axles of tractors via pressure measurement at the suspension cylinder. For unsuspended pendulum axles, the pendulum bolt or the bearing for the pendulum bolt in the axle chassis may be designed as a shear force transducer or a normal force transducer. Both components are into the force path of the axle load to the tractor chassis and therefore suitable for the position of an axle-load sensor. These systems are known for counterbalance fork lifter and described for example in DE 102006028551 A 1 (Linde Material Handling GmbH 2006).

Figure 3 shows the mounting positions of sensors for detecting wheel loads on rigid axles. DE 102009025494 A1 (Grasdorf Wennekamp GmbH 2009) describes an ultrasound sensor which is installed in the rim to measure the distance between rim and tire (Figure 3, Pos. 1). With the information of the tire inflation pressure, temperature and individual tables given by the tire manufacturers it is be possible to estimate the wheel load. Späth (2004) developed measurement wheels, which allow the measurement of forces for all three degrees of freedom (Figure 3, Pos. 2). Kistler Instrumente GmbH offers measurement wheels which can detect torques for all degrees of freedom additional to the forces (Figure 3, Pos: 2) (Schulze Zumkley and Böttinger 2009). In WO 2017/042265 A1 (Agco Int. GmbH 2016) an axle load measurement via distance measurement between axle housing and wheel flange is described (Figure 3, Pos. 3). In WO 2013/104981 A1 (Agco Int. GmbH 2013a) and Rempfer (2003) assemblies are described for rigid axles. Resistance strain gauges measure the bending of the axle housing in the consequence of the effective wheel load (Figure 3, Pos. 4). A similar system, which also uses the bending of the axle housing as active principal, is used for an overload protection system for telehandlers (Ebe Elektro-Bau-Elemente GmbH). Instead of resistance strain gauges, capacitive sensors realize a distance measurement. Wieckhorst et al. (2015) present, based on DE 102013110311 A1 (Claas Tractor Sas 2013), a traction sensing element (Figure 3, Pos. 5). This uses passive magnetostrictive sensors, assembled on the shaft of the rigid rear axle, to quantify vertical and horizontal tire forces as well as the driving torque.

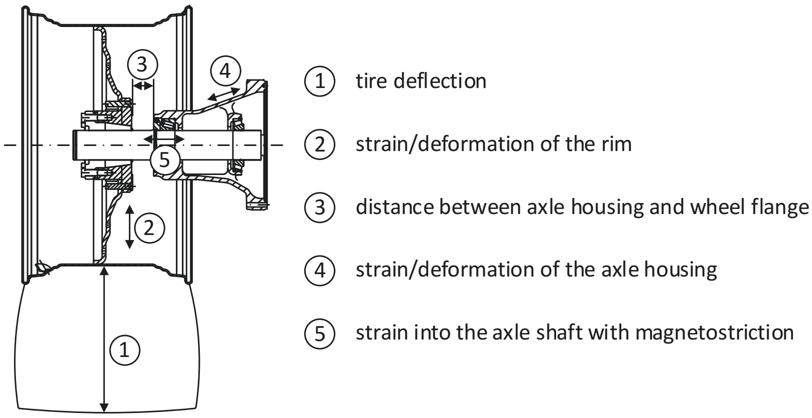

Figure 3: Possible sensor positions and principals for tire load detection on rigid axles

All listed measuring principles for rigid axles have in common that a deformation measurement or changes in a magnetic field detect strains of a component. The measured value is proportional to the change of the vertical wheel load and must be translated by a calibration function. Depending on the position of the measuring point in relation to the force application point in the tire-soil-contact, there are several interfering and influencing factors, which make the use of a calibration function more difficult. In WO2014/000932A1 (Agco Int. GmbH 2013b) the challenges in the calibration of axle and wheel load sensors are described especially for the position of the measuring point on the axle housing (Figure 3, Pos. 4). However, the problem can be directly transferred to the other measuring points on rigid axles. A linear relationship between the change of the vertical tire force and the measured value is expected, the masses of all components between the measuring point and the force application point must be added as a constant. Figure 4 shows the effects on the calibration function from different disturbances. By varying the tire/rim combination, the attachment of wheel weights (attachment to wheel bolts) or the use of water ballast in the tires, the constant load proportion in the calibration function is affected. For the measuring points Pos. 3–5 (Figure 3), the lever arm between force application point and measuring point creates a factor influencing the slope of the calibration function due to the possible track width adjustment. The use of duals requires additional measuring technology for the measuring principles 1 and 2 (Figure 3) on the additional wheels; for the measuring principle 3–5, both the constant and the linear parts of the calibration function change.

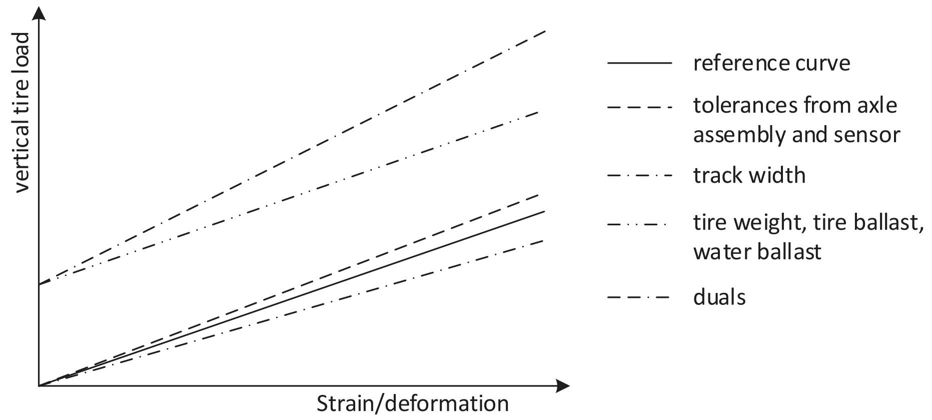

Figure 4: Impact of disturbing factors between force transmission point and tire load sensor on calibration function of the sensor, according Agco Int. Gmbh (2013b)

Used sensing principals for dynamic axle load determination

As already mentioned, pressures in the suspension system in combination with the known dimensions of the suspension cylinder can be used for axle load determination on suspended axles. The number of necessary pressure sensors depends on the number of suspension cylinders used, thus also on the kinematic structure of the axle and the hydraulic or pneumatic circuit of the cylinders. The possible hydraulic circuits for suspension systems can be seen in Bauer (2008). For hydraulically or hydropneumatically based systems, independent pressure sensors are used for each chamber of a suspension cylinder. Figure 5 shows the structure of a suspended axle with a preloaded, central positioned suspension cylinder.

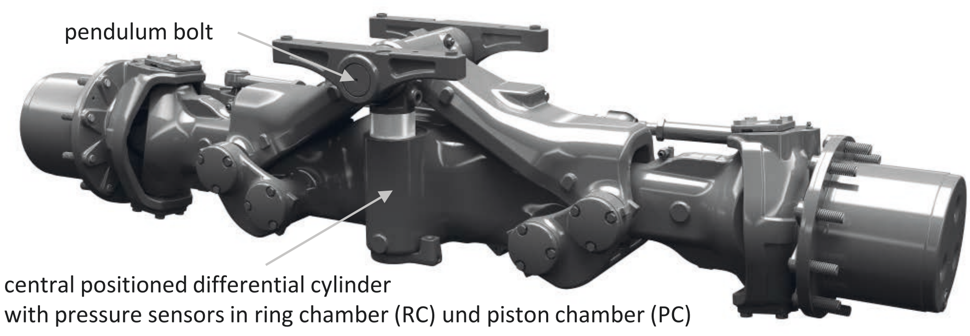

Figure 5: Assembly of a hydropneumatic suspended axle with a central suspension cylinder and pressure measurement

For the cylinder chambers, two opposing forces can be calculated according equation 1 and 2. The difference of these two forces is the resulting cylinder force (equation 3).

$$F_{RC} = p_{RC} \cdot A_{RC} \quad \text{(Eq. 1)}$$

$$F_{PC} = p_{PC} \cdot A_{PC} \quad \text{(Eq. 2)}$$

$$F_{Cyl} = F_{PC} - F_{RC} \quad \text{(Eq. 3)}$$

In order to determine the effective vertical axle load from the cylinder force, the unsuspended masses need to be added. As the suspension cylinder is positioned directly between the axle and the tractor chassis like shown in Figure 5 and the cylinder transfers the total vertical force, the cylinder force is directly proportional to the total axle load.

$$F_{Cons} = (m_{axle} + m_{tires}) \cdot g \quad \text{(Eq. 4)}$$

$$F_{Axle} = F_{Cyl} + F_{Const} \quad \text{(Eq. 5)}$$

Instead of resistance strains gauges the principle of magnetostriction detects the component stresses on rigid axles. In ferromagnetic materials, the crystal lattice results in the formation of contiguous regions with a common magnetic preferential direction, the so called Weiss area. The orientation of the Weiss areas in an unloaded component, where no external magnetic field is applied, is ideally chaotic. As a result of machining processes of the component, however, a plurality of the regions may be oriented in the same or similar directions, the component then has a self-magnetization. With an induced magnetic field into a ferromagnetic part, the Weiss areas align themselves, preferably in the direction of the applied magnetic field. This leads to a change of the length of this part, caused by the Joule effect (Figure 6). The other way around, a change in length of the part due to a load leads to a realignment of the Weiss areas along the main stress axis. This effect is called Villari Effect. The reorientation of the Weiss areas leads to a change in the magnetic field strength of an external magnetic field. The Villari effect is used to evaluate the component stress and quantify an applied load (Hering 2012).

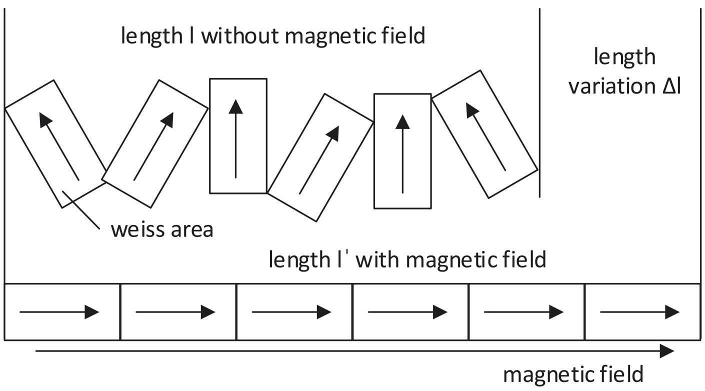

Figure 6: Joule effect: Length variation of a ferromagnetic part caused by a magnetic field (Hering 2012)

Magnetostriction needs two sensing elements. The primary sensing element is a ferromagnetic part like a shaft, the secondary sensing element is the sensor head. The required magnetic field can be coded to the ferromagnetic part or otherwise the sensor head has an integrated field coil or a Magnetization-Yoke to produce a non-permanent magnetic field. Several coils in the sensor head detect the intensity of the magnetic field.

Figure 7 shows in an exemplary way the structure of an active magnetostrictive sensor head in a top view, which is oriented orthogonally to a ferromagnetic shaft. The sensor head includes one field coil in the middle for generating a magnetic field and four sensing coils at the circumferential, which couple the magnetic field and generate a yoke effect between field coil and sensor coil. To detect changes in the magnetic field out of strains in the consequence of bending moments, the potential between two sensing coils, here H_1 and H_2, is compared.

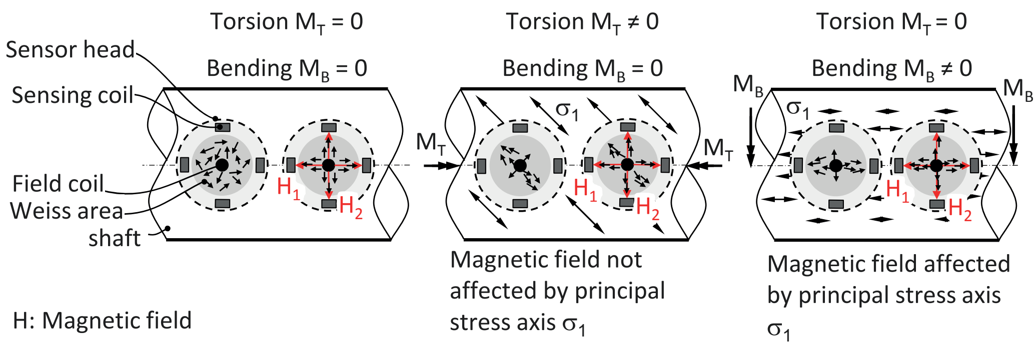

Figure 7: Functionality of a magnetostrictive bending sensor

Depending on the orientation of the sensor head, the sensor measures bending or torsional stresses. For this purpose, the sensor head is rotated about its longitudinal axis, that two opposite measuring coils are aligned along the main stress axis σ_1 of the dedicated stress. Figure 7 shows the orientation of the sensor head for measuring bending stresses. Three different stress situations for the shaft point out, that the sensor enables unique measurement of the bending load and automatically compensates torsion stress at once. Figure 7 shows on the left an unloaded shaft, in the middle a torsional stressed shaft and on the right a bending stressed shaft. For each situation, the alignments of Weiss areas in the shaft as a result of the stress are shown on the left sensor head, on the right sensor head the stress is superimposed with a magnetic field of the sensor field coil.

In the case of the unloaded shaft (Figure 7, left) the Weiss areas are aligned along the magnetic field generated by the field coil. As an equally number of regions align between the field coil and each sensor coil, the field strengths at each sensor coil are the same, so the potential between the neighboring coils is zero. In the case of a purely torsional stressed shaft (Figure 7, center), the Weiss areas are first orientated along the main stress axis σ_1, rotated about 45° with respect to the longitudinal axis of the component. With an additional magnetic field, a few regions align themselves again in the direction of the magnetic fields H_1 and H_2. Since the main stress axis is orientated exactly between the sensor coils, there is again a uniform realignment for the magnetic fields in directions H_1 and H_2. Even in this case the sensing coils measure no potential in between. For the bending-stressed shaft (Figure 7, right), as in the previous case, the Weiss areas first align with the main stress axis, in this case in the longitudinal direction of the shaft. If now the field coil applies an additional magnetic field, the alignment of the Weiss areas along the axis H_1 stabilizes, only a few regions re-orientate themselves in the orthogonal direction H_2. For this case, a potential between the two sensor coils can be measured.

Sensing unit

In order to derive the actual vertical axle load of a suspended axle from the cylinder force determined by cylinder pressures, the unsuspended masses of the axle body and the tires must be added according to equations 4 and 5. Friction influences of sealing rings between cylinder rod and cylinder housing as well as between the cylinder piston and cylinder housing disturb the determination of the cylinder force. For static axle load determination, the stick-slip effect of these seals influence the measured value, which may be minimized by sufficient lubrication. In addition to friction on the cylinder, friction occurs in several joints, depending on the axle design, which allow the desired suspension kinematics. In the present axle concept according to Figure 5, joint friction is less than the cylinder friction, since the cylinder carries the weight of the tractor front, instead of the rocker arms of the axle kinematics only carry their own weight. Another disturbance on the determined axle load occurs during driving with activated four-wheel drive. When the axle has to transmit drag forces, there is a tension in the axle kinematics, which increases the joint friction. Pichlmaier (2012) describes the influence of friction disturbances on the measured wheel/axle load at 0.25% for a single-wheel suspension system. Due to a steady movement of the cylinder while driving, influences for dynamic conditions are expected even less.

As an enhancement of the passive magnetostrictive sensor presented by Wieckhorst et al. (2015), for the integrated wheel load measurement at the rear axle active magnetostrictive sensors are used. As the biggest advantage, the active magnetostrictive sensor eliminates the magnetic coding of the primary sensor element, in this case the axle shaft. This is a decisive advantage for the industrialization of this measuring concept. The component used as the primary sensor element must be made of ferromagnetic material, have a certain surface hardening and should be degaussed along the entire circumferential. Residual magnetization in the material downgrades the quality of the applied magnetic field and worsen the measured signal. To correct the signal, especially to get valid values in static conditions, an absolute angle sensor allows an angle-dependent compensation. An integrated distance sensor compensates disturbances out of rotational non-uniformities and bending of the axle shaft. Figure 8 shows the installation of the sensor in front of the axle housing in top of the shaft, which provides an automatic compensation of the bending stresses due to drag forces of the vehicle, since the sensor is in the neutral phase for these stresses. As described above, the intelligent sensor design compensates in principle the torsional stresses occurring due to the applied drive torque to the wheel.

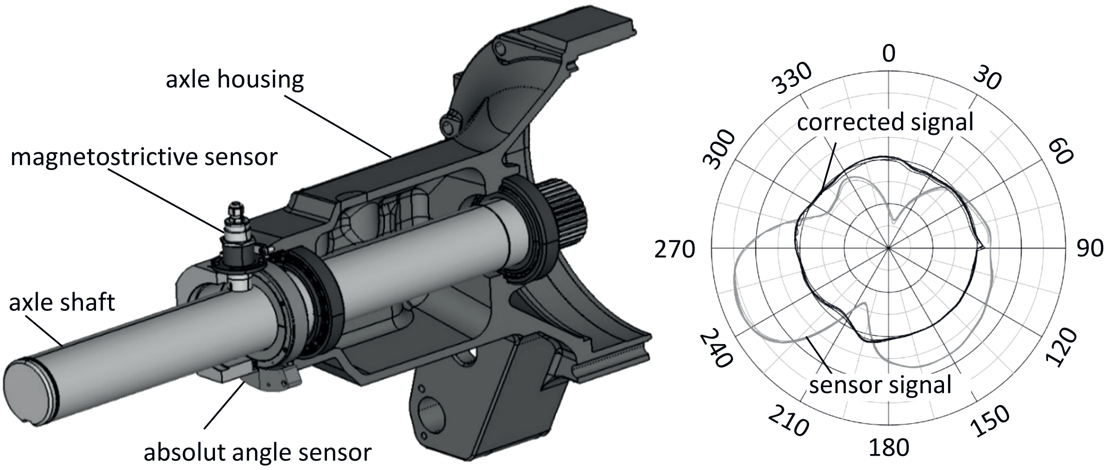

Figure 8: Sensor assembly in the rear axle housing and signal correction via an absolute angle sensor

The overall sensor unit for rigid rear axles uses a magnetostrictive sensor, installed on top of the axle shaft, mounted directly in the axle housing or using a retrofit adapter in front of the axle housing. Additionally, an absolute angle sensor is mounted on the axle shaft. For the suspended front axle, pressure sensors can be installed in the hydraulic lines of for the suspension cylinders or directly at the hydraulic block for the suspension system. An inclination sensor on the tractor body completes the sensor system, which determine the inclination of the machine in the longitudinal and lateral direction.

Validation

For the measurement system of suspended axles, the axle load and the calculated cylinder force must show a constant offset due to the unsuspended masses according to equation 5, as well as a further portion resulting from friction influences. For the validation of the measuring system, a CLAAS Axion 840 was equipped with wheel force transducers from Kistler company, which allow amongst others the measurement of vertical forces while driving. For an in-field test of the tractor, Figure 9 shows the graphs for the axle load calculated as the sum of left and right vertical wheel force, and the cylinder force calculated by equation 3. Turning maneuvers separate several consecutive work drives with a 6-furrow plough. One cycle combines two opposing work drives including two turnings. For each cycle it can be seen, that the front axle load is different for the opposite work drives, due to an inclination of the field in the vehicle longitudinal direction. The calculated difference between the axle load and the determined cylinder force is approximately constant, hence the theory from equations 4 and 5 is validated for dynamic conditions. In standstill it is recommended to measure after a movement of the cylinder, e. g. realized by deactivation and activation of the suspension system, for minimization of influences from stick-slip effect.

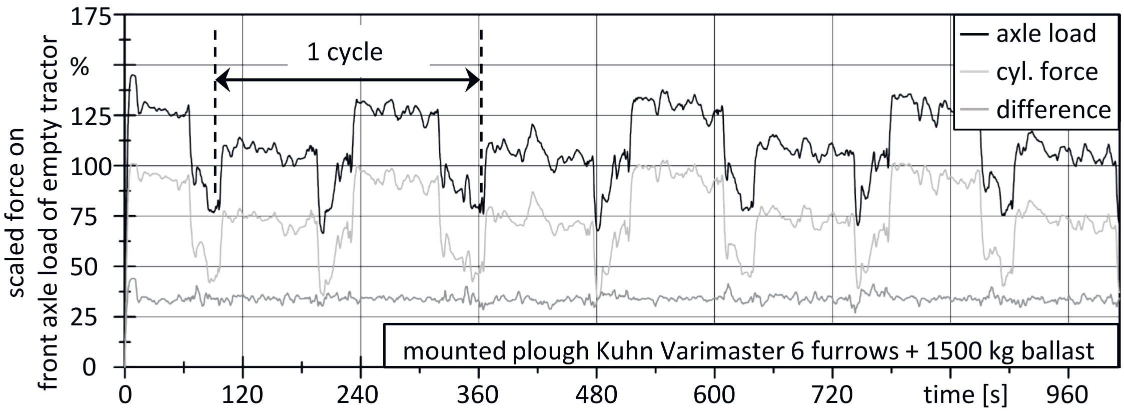

Figure 9: Difference of axle load and calculated cylinder force, measured with an Axion 840 equipped with a 6 furrow plough and 1500 kg front ballast

For the rear axle sensors first validation measurements were done with a simplified sensor unit on a CLAAS Arion 550, without absolute angle sensors and only on the right side of the machine. To calibrate the sensor, tractor ballasting simulates different wheel load conditions. The static wheel weights are measured by using a scale. Afterwards, the tractor performs a slowly test-drive on a flat road surface with constant speed (about 2 km/h) over several wheel revolutions. Adjusting the recorded mean value of the sensor to the static wheel weight, offers the opportunity to filter dynamic influences from the rotating shaft for longer measurements.

Field tests with a mounted cultivator show the behavior of the sensor during soil cultivation. Due to missing reference measurement technology on the wheel, the sensor-determined wheel load curves can initially only be checked qualitatively. Figure 10 shows measurements of the wheel load for several work drives. The individual work drives are interrupted by turning maneuvers, in the turning maneuver the speed decreases to values less than 5 km/h. The vertical forces rises while working because of process forces, hence the rear axle load rises, too. For the turning maneuvers, the measurement log shows an unloading of the rear axle. The increase of 30–40% of the rear wheel load during the working drives compared to turning seems to be quite realistic according to the resulting change in axle load distribution due to drag forces and the transfer of vertical forces of the cultivator to the tractor.

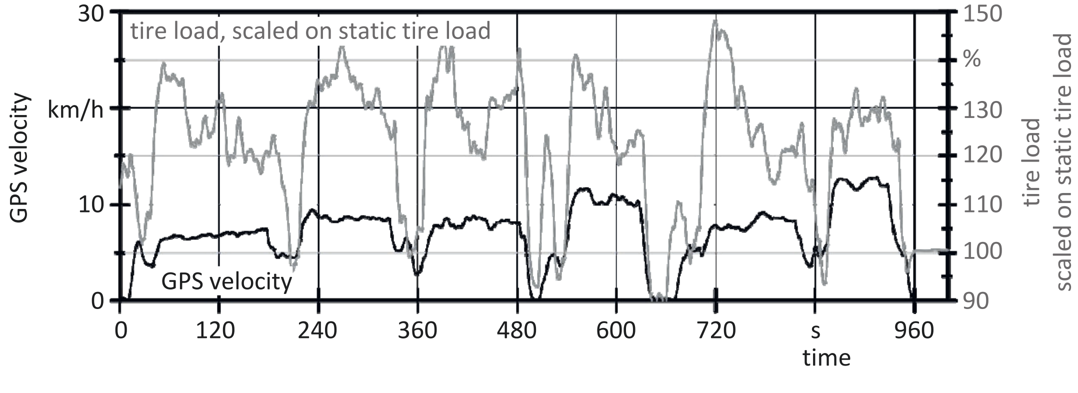

Figure 10: Load on the rear right tire of an Arion 550 equipped with a semi-mounted cultivator and 900 kg front ballast

Conclusions

In order to avoid soil compaction when using tractors on agricultural soils, the vehicle mass and tire inflation pressures must be set to the lowest possible value and matched to one another. The targeted distribution of vehicle mass on the wheels according to the ratio of the projected tire contact area allows the setting of the same tire inflation pressure on all tires. In order to determine the resulting tire forces during work at all time, a wheel load measuring system integrated into the vehicle structure is necessary. For a standard tractor with hydropneumatically suspended front axles, a measuring system can be implemented using pressure sensors in the suspension system and magnetostrictive sensors for rigid axles. The determination of the front axle load within this measuring system has been validated with reference measurement technology. On the rear axle, a calibration function in static conditions was determined for the measuring system, the measured signals in the subsequent field test was verified using empirical and expected values. A validation of the rear wheel vertical load measurement using reference measurement technology is still pending.

For magnetostrictive stress detection as well as for other wheel load measuring methods on rigid axles, many disturbing factors have to be taken into account. Configuring the tractor with wheel ballast or duals demands different calibration functions. In addition, the sensor system requires an actual value for the trackwidth and the used tire-rim combination. Providing a prompt in an operator terminal can replace further sensors to get this necessary information. Via stored tire load pressure tables, the known wheel forces and a tire inflation system, it is possible to operate the tires to full capacity at any time and to ensure soil-protecting use of the machine.

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