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Estimation of Soil Pressures Based on the Pressures in the Hydraulic System for a Legged Forestry Machine

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Abstract:
Harvesting operations with wheeled forestry machines can bring great harm to wet soils due to the machine weight and wheel slip. Factors such as the reduction of wheel slip, machine weight and total area affected by forestry machines are crucial in protecting soils. The accurate measurement of the pressure introduced by forestry machines to the soil, without harming the structure of the ground nor making assumptions of the tire or ground behavior, poses a challenge. Within this article a method to calculate the contact soil pressure, of a portal advancing mechanism for sensitive soils is presented. The results are then further evaluated based on simulative results. B y using the kinematics of the legged machine, it becomes possible to determine the soil pressure without making rough assumptions of the legs or the ground. The kinematic allows to measure the forces of the hydraulic actuators that are holding the legs in position. Through this, a direct calculation of the force which is transferred to the ground can be made. To determine the forces of the hydraulic actuators in a movement cycle, a coupled simulation of the kinematic and hydraulic system is set up. Using the determined pressures in the cylinders the exerted force on the ground is calculated. The developed calculation method has been set up in such a manner that the results can easily be compared to real world test data in future studies. In addition, the effects of this particular legged forestry machine on the ground will be compared to other machine types under the consideration, that with this new concept no slip is expected. Using this approach, the soil pressure and the impact on the ground of a legged forestry machine can be evaluated in an early stage of development.

Keywords: portal advancing mechanism, soil pressure, simulation, hydraulics

1. Introduction

Wood as a sustainable construction material and energy source is gaining an increasing importance in the public. Therefore, sustainable forestry operations are also gaining in importance. For sustainable forestry operations it is necessary to reduce soil damage as much as possible, because this damage has a direct influence on the productivity of the surrounding forest (Williamson and Neilsen, 2000; Cambi, Certini, Neri, Marci, 2015). To reduce damage on sensitive soils, the harvesting season takes place during cold periods while the ground is frozen (Rittenhouse, Rissman, 2015). With cold periods becoming rarer (Rittenhouse, Rissman, 2015), it is important to develop forestry machines which can harvest all year long.

In fully mechanized forestry operations with wheeled and tracked forestry machines, sensitive soil gets damaged through machine weight as well wheel or track slip. Soil damage will be higher in areas consisting mostly of wetlands in comparison to areas with dyer and firmer ground (Cambi, Certini, Neri, and Marci, 2015). By reducing the weight of forestry machines, the induced damage can be reduced as the compaction of the soil is minimized. One issue of compaction is its negative effect on the ability of the ground to absorb water (Cambi, Certini, Neri, and Marci, 2015). A second possibility to minimize the negative effects of forestry machines on the environment is the reduction of slip between drivetrain and ground, resulting in less tearing of the ground. Current research is mainly focused on developing technologies to reduce the slip (FNR, 2021a). Non-wheeled or tracked machines present the most promising technologies, as the machines have the potential of reaching zero slip. With no slip and only a compaction of the ground at specific points instead of along the entire skid lane, regeneration rates will be higher, and the forest can grow in a more sustainable and healthy way (Williamson and Neilsen, 2000; Cambi, Certini, Neri, and Marci, 2015). Furthermore, this can lead to more robust forests against environmental influences like erosion, as ruts on the skid track, which are known to increase erosion, are removed (Christopher and Visser, 2007). (FNR, 2021b)

For state-of-the-art wheeled machines, accurately determining the contact pressure of tires requires a great effort, because the contact area depends, among other things, on the dynamic tire diameter (Marusiak and Neruda, 2018). Different methods exist to quantify the impact of forestry machines on the soil. For example, in (Marusiak and Neruda, 2018) different models for calculating the contact pressure were compared with measurements made by sensors which were built into to the ground under the skid trail. With this measurement method it is only possible to get a contact pressure at a specific point of the trail. Also, the modeled pressures differ from each other as well as from the measurements made by the sensors. A further method to evaluate the pressure introduced to the ground is presented in (Nolting, Brunotte, Lorenz and Sommer, 2006). In this study, a hole beside the skid trail had to be dug, as to be able to set the pressure sensors under the skid trail. This method is invasive and limited to a specific point on the skid track, whilst also providing measurements of pressure in different depths (Horn, Vossbrink and Becker, 2004; Riggert, Fleige, Kietz, Gaertig and Horn, 2016). Altogether one can say, that there is not an established non-invasive method in literature to determine accurately contact pressures.

In this article, the effects of the portal advancing mechanism on the soil is evaluated. In contrast to wheeled machines, it can be assumed, that the introduced vertical forces of such a movement mechanism are the main reason for soil damaging effects. To quantify the impact of the portal advancing mechanism, the pressure introduced through the feet of the machine need to be determined. Using the kinematics of the machine, a theoretical calculation model is developed, with which the ground forces can be derived from the pressures in the hydraulic actuators. As this movement mechanism is still in a early stage of development, real world measurement data cannot be used to validate the theoretical calculation methods of the ground impact. Therefore, a simulation is used to generate first data and to validate the developed calculation method. Finally, the determined ground pressures of the portal advancing method are compared with values of other forestry machines found in literature.

2. Portal Advancing Mechanism

In this work the portal advancing mechanism is considered, which is a non-bionic principle for locomotion on sensitive wet and flat soils. The movement mechanism emerged out of the development of the so called “Portalharvester” in (Knobloch, 2017). The walking frame consists of two bases (“standing bases”, SB), each with three hydraulic controlled legs, and a traversing bridge, which has an folding joint in its middle, connecting the two bases, as can be seen in Figure 1. A moveable upper carriage equipped with an engine and a forestry crane is mounted onto the bridge. As the legs of the mechanism are hydraulically telescopic, they take up as little space as possible during the walking process and keep the center of gravity close the top of the base. The bridge’s inclination can be adjusted by ± 10 degrees at each base to compensate for a slope of the terrain. The portal advancing mechanism allows to move over terrain without wheel slip, so that only vertical forces must be compensated by the forest soil. Furthermore, the ground area that is affected by the machine is reduced in comparison to a state of the art wheeled or tracked forestry machine. (Knobloch, 2017)

Figure 1. Representation of the portal advancing mechanism with a harvester crane. (Knobloch, 2017)

2.1 Movement Cycle of the Portal Advancing Mechanism

To get a better understanding of the machine and the impact on the ground, it is necessary to first understand the movement sequence the machine goes through to complete one full step. First of all, the upper carriage is moved over one base, so that the half of the bridge opposite to the upper carriage can be folded up using the joint located in the middle of the bridge. In this configuration the bridge can rotate around the vertical axis of the base located bellow the upper carriage. To fulfill one complete step, the bridge is unfolded after the rotation is complete. All six legs are once more in contact with the ground again. Thus, the movement cycle can be divided into four parts:

1. Moving the upper carriage ($t = 2 \ldots 7\ s$)
2. Folding the bridge ($t = 8 \ldots 23\ s$)
3. Rotating the bridge ($t = 23 \ldots 32\ s$)
4. Unfolding the bridge ($t = 32.5 \ldots 44\ s$)

The normalized positions of all actuators involved in the movement for one full step are shown in Figure 2. As the movements of the three legs of one base are all parallel, they are shown as a single actuator (“Leg Cylinder”). It takes 42 seconds to complete a full step. In the first movement step, between $t = 2 \ldots 7\ s$ all six legs of the portal advancing mechanism are on the ground. As the inclination actuator moves out between $t = 8 \ldots 12$ s the three legs opposite to the upper carriage are lifted. In the time after that ($t = 14 \ldots 18$ s) the airborne legs are folded up. All the weight of the machine now remains on the opposite three legs. While the bridge is folded ($t = 18 \ldots 23$s), the machine’s center of gravity moves to the rotation axis of the base. In consequence the complete weight will be distributed more equally onto the legs. The rotation starts after the folding is complete at $t = 23$ s. The bridge starts in a position between two legs and ends, after 9 seconds of rotation, over the third remaining leg at $t = 32$ s. After the rotation of the bridge is complete, the bridge starts to unfold itself. During the descent of the bridge, the extraction and lowering of the three airborne legs begins. At $t = 44$ s, all six legs are on the ground again and the load of the machine is once again carried by all six legs.

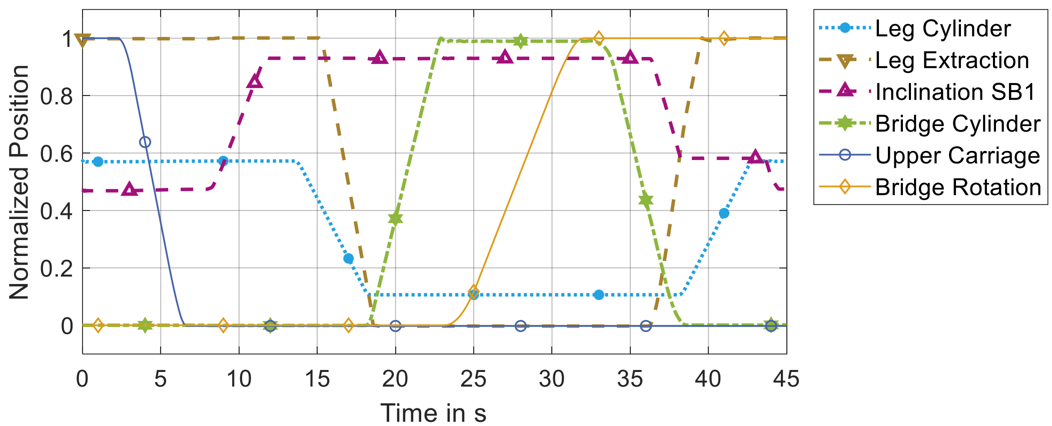

Figure 2. Relative positions of the actuators through one movement cycle.

3. Model Development and Comparison

3.1 Kinematic-based Calculation Method

To determine the relation between ground force and the hydraulic cylinder force, a free cut of the leg is made. The acting forces on the leg are depicted in Figure 3. At point A the leg is attached to the base. On the right side, the contact to the ground through a foot is simplified as shown. It is assumed, that the force vertical to $F_{z\,Foot}$ and $F_{r\,Foot}$ has no impact on the cylinder force and therefore this simpler 2D view can be used.

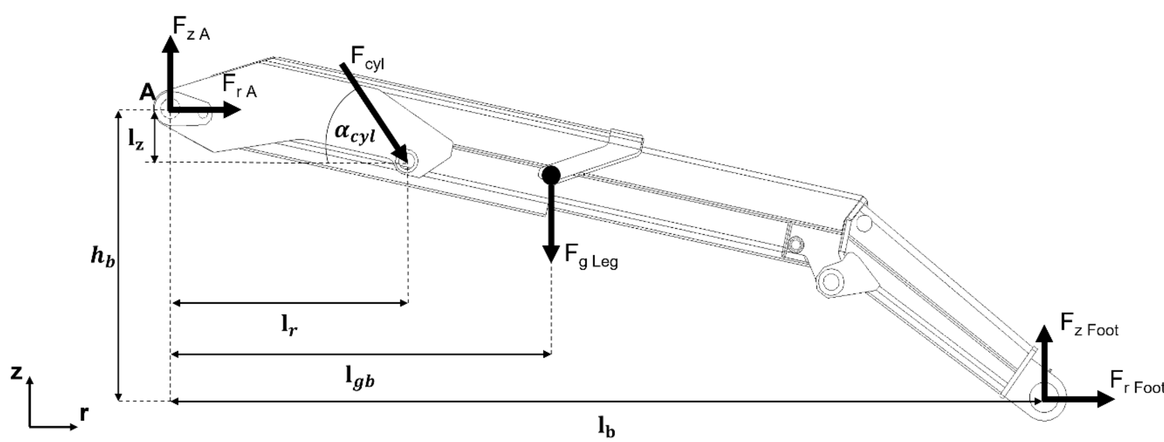

Figure 3. Free cut of one leg of the portal advancing mechanism

To determine the relation between hydraulic pressures in the hydraulic cylinder and the ground force $F_{z_{Foot}}$, only the equilibrium of torque around point A is used. The equilibrium can be written as follows:

$$0 = F_{z_{Foot}} l_b + F_{r_{Foot}} h_b - F_{g_{Leg}} l_{gb} - \sin(\alpha_{Cyl}) F_{cyl} l_r + \cos(\alpha_{cyl}) F_{cyl} l_Z \quad (1)$$

α_{cyl} describes the angle in which the cylinder stands relative to the r-axis, $F_{g_{Leg}}$ the weight force of the leg, F_{r,z_A} the bearing forces of the leg and $F_{r,z_{Foot}}$ the simplified ground forces of the foot.
The different distances l_i are defined in Figure 3. This equation does not yield one clear result. Therefore, the following second assumption is made: It can be assumed that all horizontal forces of the portal advancing mechanism, caused by inertia, are taken up by the force vertical to $F_{z_{Foot}}$ and $F_{r_{Foot}}$. Using this assumption, $F_{z_{Foot}}$ can be calculated and the force along the r-axis of the ground becomes zero:

$$F_{r_{Foot}} = 0 \quad (2)$$

To calculate the force of one cylinder the following equation is used:

$$F_{cyl} = p_{piston} A_{piston} - p_{rod} A_{rod} \quad (3)$$

By rearranging equation (1) and taking (2) and (3) into account, the wanted relation between the vertical ground force and the hydraulic pressures can be determined by using the following equation:

$$F_{z_{Foot}} = \frac{(p_{piston} A_{piston} - p_{rod} A_{rod})(l_r \sin(\alpha_{Cyl}) - l_z \cos(\alpha_{cyl}))}{l_b} + \frac{l_{gb}}{l_b} F_{g_{Leg}} \quad (4)$$

The contact pressure p_{ground}, which is introduced to the ground by the force $F_{z_{Foot}}$ of a single leg, can easily be calculated by dividing the force by the area of a foot A_{Foot}:

$$p_{ground} = \frac{F_{z_{Foot}}}{A_{Foot}} \quad (5)$$

To further simplify the system, the changes of distances, induced by a change in the length of the hydraulic cylinder, based on the compression of the hydraulic fluid, is assumed to be so small, that it can be neglected. Consequently, all distances l_i and the angle of the cylinder in Figure 3 are assumed to be constant.

With the developed equation, the pressure introduced to the ground by one foot of the portal advancing mechanism can be calculated through the hydraulic pressures in the cylinder of a leg. To evaluate the calculation method without real world data a simulation of the movement mechanism is used. The simulation is shortly described in the following section.

3.2 Simulation Model

To reduce development time and to avoid expensive mistakes a co-simulation is a proven tool in the product development process (Marthaler, 2021; Völker, 2011). To model the mechatronic system of the portal advancing mechanism, a holistic simulation model is set up. It consists of a multibody model of the kinematics coupled with a model of the hydraulic drive train. Such a coupled simulation has advantages in the modelling and the computing efficiency (Völker, 2011). In coupled simulations, each sub-model can use a specified solver for its task. The communication between the sub-models is managed by a master-solver. The system is coupled by the exchange of the system variables *force* and *position/velocity* between the two sub-models. Thereby, the movements of all joints are calculated in the multibody model under the effect of external forces. The calculated positions and velocities are then handed over to the model of the hydraulic drive train, where parts of the external forces are calculated and returned to the multibody model. (Völker, 2011)

Starting point for the parametrization of the model is the geometrical data of the mechanism and manufacturer specifications for the hydraulic actuators. This results in the dimensions for the kinematics, as well as the weight of the bodies. For the multibody model only motion relevant rigid bodies are used and reduced to simple geometrical shapes. These are then parametrized with the corresponding mass. In the hydraulic model only the cylinders for the legs and the inclination are modeled to reduce the complexity of the simulation. The pressures in each chamber of the cylinders are directly measured through attached sensors. The movement of the hydraulic actuators is controlled by simple time-depended signals, to create the wanted movements. These signals represent the openings of the valves and therefore the velocities of the hydraulically operated actuators. With only three of the six functions necessary for one movement cycle modeled in the hydraulic part, the other actuators must be controlled directly by a signal which represents the movement. To get these movements, separate simulations were run with simplifications like the neglection of the ground contact. The results of these simulations were then used as the movement input for the joints. Thereby, the input for the bridge cylinder was modified with a transfer function with PT1 behavior to get a more realistic movement.

The ground contact of the portal advancing mechanism is modeled through a spring-damper-model in the vertical axis for each leg. Additionally, a simplified friction model with stick-slip effect is incorporated for the horizontal axes. The spring rate represents the toughness of the ground. For the generation of the first data, a flat and hard ground, like a paved surface, is assumed to reduce relative movements of the mechanism introduced through the compression of the springs. Therefore, the spring rate is chosen in a manner that the spring compresses about $0.2\ mm$ when the maximum force of a leg acts on it.

3.3 Postprocessing of Simulation Results

To determine the most time-efficient and accurate simulation setup, the relative tolerance of the master-solver of the co-simulation was set to either $1e-03$ or $1e-05$. The value of the vertical ground force over time is used to compare the simulation setups, as can be seen in Figure 4.

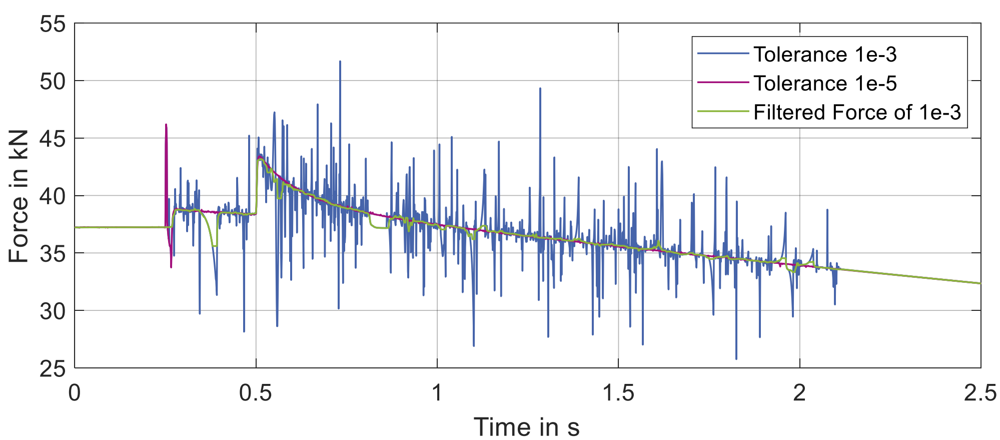

Figure 4. Comparison of simulation result of the vertical ground force over time for two relative error tolerances of the solver and a filtered output.

The overall value of the ground force decreases with a very similar slope in both the simulations with the higher and lower relative tolerance. However, the simulation with a relative tolerance of $1e-03$ shows a large number of numerical artefacts and impulsive jumps. A reason for this might be due to the fact, that the ground model is based on a spring-damper-model, which introduces substantial changes in force through little movements, or the sensitivity for oscillations of the solver.

To keep the computing time low, in this case about 72 hours, whilst also achieving a result, which can be compared to the results of the previously developed calculation model, the simulation results with the higher tolerance of $1e-03$ are filtered. The impulsive jumps in the signal can be seen as noise. To smooth out the noise and to preserve the sharp edges in the curve, a moving median filter is used. This filter can smooth out the impulsive noise and preserves sharp edges (Lawrence, Sambur, and Schmidt, 1975; Micek and Kapitulik, 2003). The result of this filter is pictured as a green line in Figure 4. The result of the applied filter is very similar to those with the lower tolerance of $1e-05$ (red line). Only in places where the unfiltered blue curve constantly differs to the red curve, the filtered values also deviate. The filter response also follows the jump at $t = 0.5$ s. The generated data using a relative tolerance of $1e-03$ and a moving media filter are sufficiently good enough for a comparison between the result of the calculation method and the filtered simulation result, leading to a drastic reduction of computing time in comparison to the simulation run with the lower tolerance. Therefore, for the rest of this study, a relative tolerance of $1e-03$ and a postprocessing step with a moving median filter is used for the generation of simulative data.

3.4 Comparison of Calculation Method and Simulation Results

To verify the assumptions that were made in section 3.1, the obtained values for the ground force of the leg with the highest load, calculated with equation (4), are compared to the simulation results. In the following all pressures used for the calculation method are obtained from the sensors in the simulation model. The values of the ground force determined by the calculation and simulation are plotted in the upper half of Figure 5. The difference between the values of both models is depicted in the lower half.

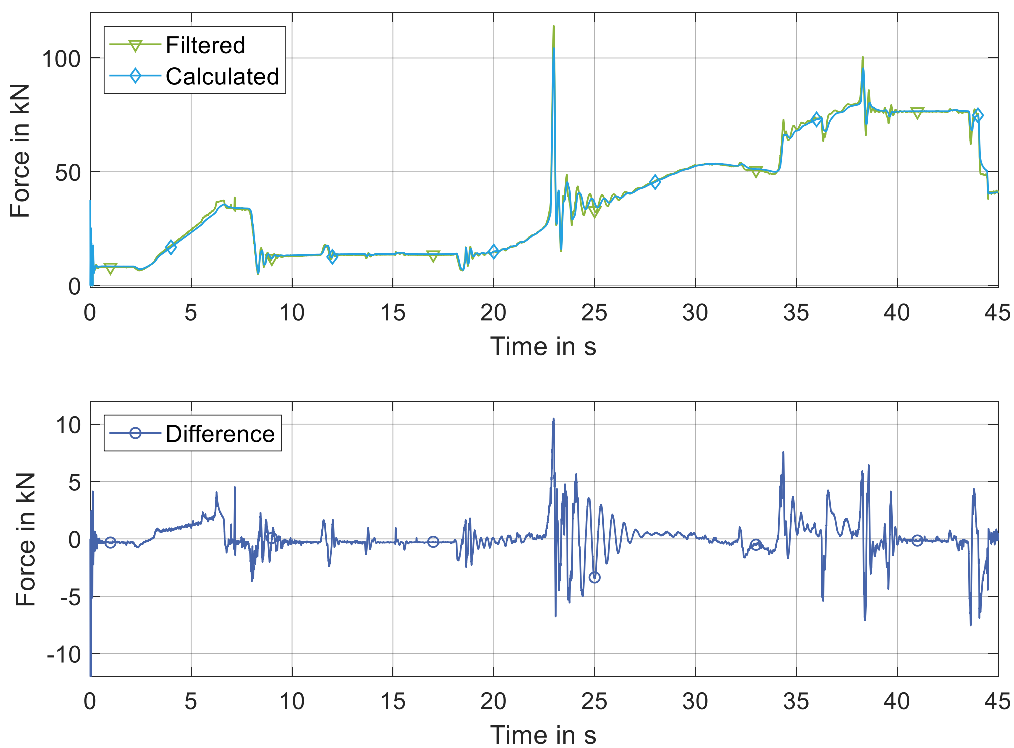

Figure 5. Comparison between the filtered and calculated ground force for the leg with the highest load their difference

The results of the calculation method (eq. (4)) match the results of the simulation to a large extend. At the beginning of the simulation, while the upper carriage is moving and the bridge is folded ($t = 1 \dots 22$ s), the difference lies between ± 5 kN. Also, similar oscillations can be observed. At $t = 23$ s the biggest deviation of 10.5 kN can be seen. Here, the calculated force reaches a lower value in comparison to the simulated force. This peak happens at the end of the folding movement of the bridge. During this movement, the rotating mass is slowed down and oscillates for a short period of time in the hard stop of the bridge cylinder.

One possible reason for the calculation value to deviate from the simulation is that in the calculation it is assumed that the hydraulic cylinders have rigid distances. In contrast to this, the cylinder can change its length in the simulation, in dependence of the compression of the hydraulic fluid. A further reason for the error could be that for all distances in the calculation the values are rounded. Another likely reason for the errors could be the friction model, which is implemented for each cylinder. In this model, a viscous damping and a static friction force is added to the system, whereby the pressure build-up in the cylinder chambers is influenced with an additional external force. This additional force also influences the pressure level in the cylinder. Therefore, the total force acting along the cylinder is different to the calculated force that is only based on the pressures and the cylinder cross sections.

Boxplots of the deviations for all 6 ground forces are shown in Figure 6. The bases and foots are abbreviated in the following manor: Base: $SB_{1,2}$ and Foot: $F_{1 \dots 6}$. As, during the first second, the simulation is in its settling process and the movement only starts after $t = 2$ s, the first second is not considered in Figure 6. The boxplots of the three feet of base 2 (SB2 F1 – SB2 F3) are dominated by outliers, because for 80 % of the time they are up in the air and have no contact to the ground. For the other three feet, 50 % of all deviations are lower than ± 1 kN and over 95 % are under the ± 3.6 kN mark. In general, the forces calculated with the hydraulic pressure for the three feet of SB1 reach higher values than those obtained from the filtered simulation results. In total, the mean of the calculation lies at 90 N and the median at 240 N above the forces generated simulatively. The greatest deviation can be found at the first leg of SB1, where a force 10.5 kN lower and a force of 7.55 kN higher than the simulated force was calculated.
These differences could mainly be based on the friction model for the hydraulic cylinder, as explained above.

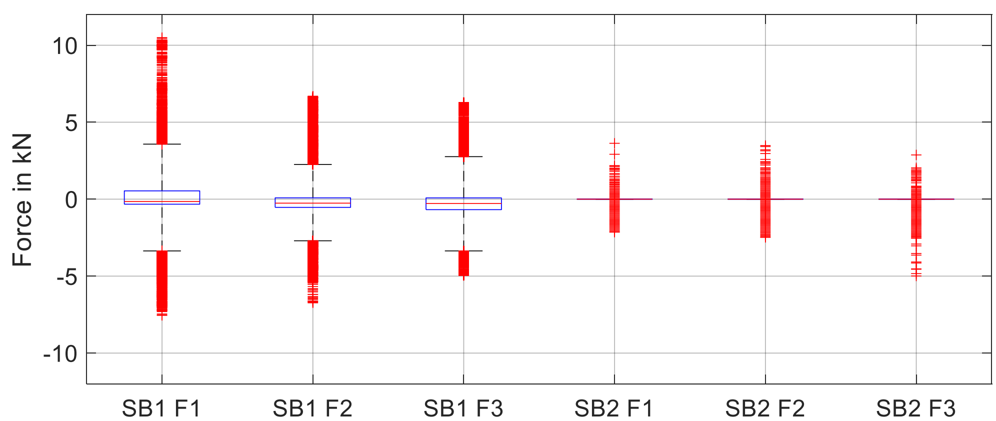

Figure 6. Difference between the calculated and filtered ground force for each foot.

Overall, the deviation between the calculated and simulated values are relatively small. Furthermore, Figure 6 shows, that the assumptions made in section 3.1 only lead to marginal differences between the calculation and simulation results. Therefore, the following results are based on the calculation method using the hydraulic pressures, as this model will allow for direct comparison with real-world prototype data in future studies.

4. Results of the Calculation Method

4.1 Estimation of the Soil Contact Pressure

In this chapter the results of the calculation model is presented. A cross section area of $0.33\ m^2$ for each foot is assumed to calculate the pressure from the ground force (see eq. (5)). The results for one movement cycle as described in section 2.1 is pictured in Figure 7. The corresponding forces can be seen in Figure 8. The movement of the upper carriage along the bridge between $t = 2\ldots7$ s can easily be identified by the swap of the load from base 2 to base 1. While every foot has ground contact, the pressures for the feet of the corresponding base are similar. Each foot reaches a maximum pressure of around 120 kPa. After the bridge is lifted, the pressure values rise to 180..190 kPa, as the load is now only distributed between three contact points to the ground. While the bridge is folded up ($t = 18\ldots23$ s), the pressures of the two feet under the bridge decreases while the pressure for the third, oppositely positioned foot increases. The load is split more equally between the three legs than during the period, in which the bridge is lifted, but not folded. This is due to the fact, that the center of mass now lies closer to the mid of the base than before. The oscillation, introduced by the deceleration of the bridge at $t = 23\ s$, creates a peak contact pressure of over 310 kPa. During the 180 degrees rotation of the bridge between $t = 23\ldots32$ s , the load distribution between the three feet changes. The bridge is now positioned above one single leg (SB1 F1). The highest nearly constant contact pressure of one entire movement cycle can be found here ($t = 40\ldots43\ s$) as this leg takes up most of the load. Through the positioning of the center of mass over one leg, a pressure of around 230 kPa is introduced to the ground until the bridge is completely lowered, and all six feet take up the load once more at $t = 44$ s.

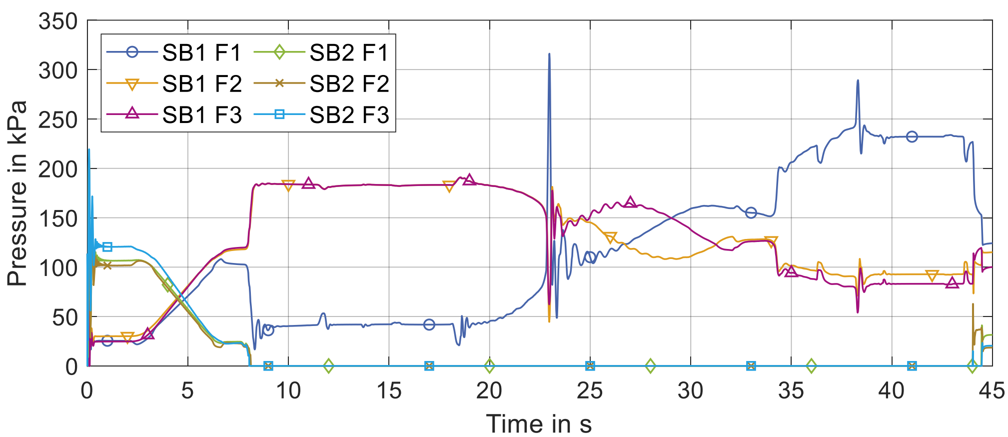

Figure 7. Introduced soil contact pressures of the legs of the portal advancing mechanism during one entire movement cycle calculated with the pressures in the hydraulic system.

4.2 Discussion of the Results

To evaluate the impact of the portal advancing mechanism on the ground, the calculated contact pressures are compared to values found in literature. During one movement cylce, a peak pressure of 310 kPa and a near constant pressure over 5 s of around 230 kPa can be observed.

A wide range of different types of forestry machines have been investigated in literature. The weight of these machines range from 650 kg for a horse to 45 t for a chain-tracked harvester. In (Horn, Vossbrink and Becker, 2004) this range was investigated and maximum contact pressures between 80 kPa and 180 kPa were reported. Similar pressures were determined by (Marusiak and Neruda, 2018) for a wheeled forwarder with a maximal mass of around 10 t. In this study pressures between 100 kPa and 240 kPa were reported. For wheeled machines forestry machines with total masses between 24 to 28 t (Riggert. Fleige, Kietz, Gaertig and Horn, 2016) reported mean contact pressures between 89 kPa to 216 kPa. With around 310 kPa the maximum peak contact pressure of the portal advancing mechanism reaches higher values than found in literature. Furthermore, the near constant contact pressure of around $230\ kPa$ lies in the upper range or even above the values found in literature.

With no slip expected, the shear stress of the portal advancing mechanism can be predicted to reach values near zero or even zero. The major principal stress of the walking mechanism is therefore the contact pressure previously determined. When these values (230…310 kPa) are compared to literature values for the major principal stress, it can be seen, that the mechanism considered in this study introduces a comparatively lower stress to the ground. In (Riggert. Fleige, Kietz, Gaertig and Horn, 2016) principal stresses up to 526 kPa were calculated, whilst in (Horn, Vossbrink and Becker, 2004) the values range from 300 kPa to over 500 kPa. The values from literature are about 2 times higher than the ones presented in this study, if only non-peak pressures are considered. Therefore, it can be expected that the impact of the portal advancing mechanism on the ground is lower than that of classical forestry machinery. If the affected surface is additionally considered, the damage potential to the ground is decreased even further.

5. Conclusions

This article presents a calculation method to determine the contact pressure of a portal advancing mechanism. Results of the calculation method were compared to simulative results. Through this comparison, the calculation approach is verified, and it can be shown, that this approach achieves good results. The calculation shows that the considered legged forestry machine stresses the forest soil with a contact pressure of up to 230 kPa and over 310 kPa in peak points. This peak pressure depends on oscillations introduced to the hydraulic-mechanical system through acceleration or deceleration of the system during the movement cycle. The calculated pressures were compared to values from literature for common forestry machines. From this comparison, it can be expected that the ground in general will be less stressed and less damaged, because no slip occurs.

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References

Cambi, M., Certini, G., Neri, F. and Marci, E., (2015), "The impact of heavy traffic on forest soils: A review", Forest Ecology and Management, 338, 124-138

Christopher, E. A. and Visser, R., (2007), "Methodology for evaluating post harvest erosion risk for the protection of water quality", NZ Journal of Forestry, 20-25

FNR (Fachagentur Nachwachsende Rohstoffe e.V.), (2021a), "Verbundvorhaben: Portalschreitwerk als Fortbewegungsprinzip auf befahrungssensiblen Böden und zerklüfteten Untergründen; Teilvorhaben 2: Entwicklung der Steuerungsarchitektur - Akronym: Portalschreitwerk", https://www.fnr.de/index.php?id=11150&fkz=2220NR216B

FNR (Fachagentur Nachwachsende Rohstoffe e.V.), (2021b), "Bodenschutz im Wald", https://mediathek.fnr.de/bodenschutz-im-wald.html

Horn, R., Vossbrink, J and Becker, S., (2004), "Modern forestry vehicles and their impacts on soil physical properties", Soil & Tillage Research 79, 207-219

Knobloch, C. (2017) Entwicklung und kombinierte Verwendung eines Portalharvesters und eines mobilen Seilkransystems in forstlichen Verfahren zur vollmechanisierten Holzernte auf befahrungssensiblen, ebenen Standorten, Dresden

Lawrence, R. R., Sambur, M. R. and Schmidt, C. E., (1975), "Applications of a Nonlinear Smoothing Algorithm to Speech Processing", IEEE Transactions on acoustic, speech and signal processing, Vol. ASSP-23, No 6, 552-557

Marthaler, F. (2021). "Zukunftsorientierte Produktentwicklung – Eine Systematik zur Ableitung von generationsübergreifenden Zielsystemen zukünftiger Produktgenerationen durch strategische Vorausschau", Dissertation, Karlsruhe. Forschungsberichte / IPEK, Institut für Produktentwicklung am KIT: Systeme, Methoden, Prozesse; 137

Marusiak, M. and Neruda, J., (2018), "Dynamic Soil Pressures Caused by Travelling Forest Machines", Croatian Journal of Forest Engineering, 39, 233-245

Micek, J and Kapitulik, J, (2003), "Median Filter", Journal of Information, Control and Management Systems, 51-56

Nolting, K., Brunotte, J., Lorenz, M. and Sommer, C., (2006), "Bodenverdichtung: Bewegt sich was? – Setzmessungen im Unterboden unter hoher Radlast", LANDTECHNIK. 61, 4

Riggert, R., Fleige, F., Kietz, B., Gaertig, T. and Horn, R., (2016), "Stress Distribution under Forestry Machinery and Consequences for Soil Stability", Soil Science Society of America Journal, 80, 38-47

Rittenhouse, C. D. and Rissman, A. R., (2015), "Changes in winter conditions impact forest management in north temperate forests", Journal of Environmental Management, 149, 157-167

Völker, L., (2011), "Untersuchung des Kommunikationsintervalls bei der gekoppelten Simulation", Dissertation, Karlsruhe. Karlsruher Schriftenreihe Fahrzeugsystemtechnik, Bd. 6, KIT Scientific Publishing, 2011.

Williamson, J. R. and Neilsen, W.A., (2000), "The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting", Canadian Journal of Forest Research 30, 1196-1205

Appendix

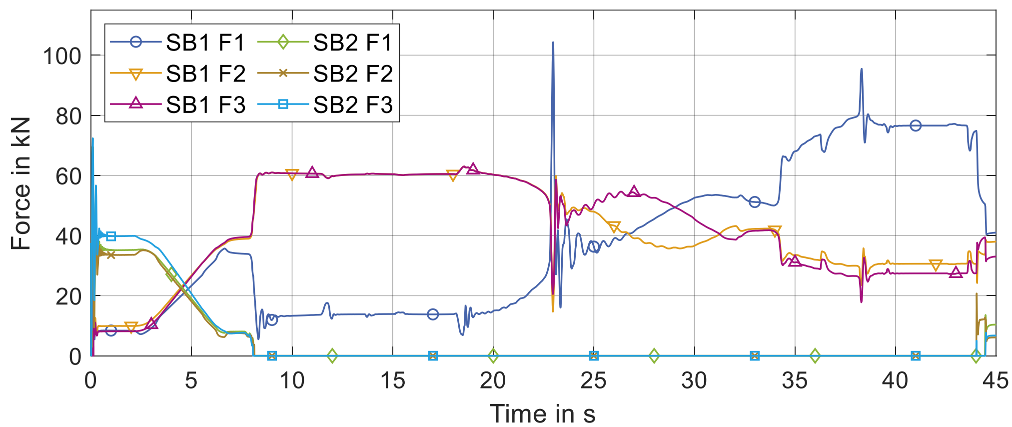

Figure 8. Ground forces through the movement cycle