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Semi-active suspension system for hydro-pneumatic full spring mounted tractors

Not only the driving and operating speed of agricultural tractors but also the ratio of transport is increasing constantly. Because of that, higher driving safety and improved driving comfort are required. To achieve this, the tractor chassis suspension has to be adapted. Based on a tractor with conventional rigid axles, a new hydro-pneumatic chassis suspension for front and rear axle, including a set of sensors, hydraulic actuators and an electronic real-time controller, was developed. The used semi-active control algorithm of the damping ratio is based on the continuous Skyhook theory. Consequently, the chassis suspension can be adjusted to any kind of road and speed to achieve an improved driveability.

Keywords
tractor, driving safety, driving comfort, semi-active suspension, hydro-pneumatic

Abstract
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In agriculture, tractors are increasingly used for transportation purposes. The maximum driving speed increases constantly. Current tractors reach velocities of up to 80 km/h on public roads. To guarantee a sufficient level of driving security while achieving high comfort, the suspension of a vehicle becomes more and more important.

Next to seat and cabin suspension, modern tractors are equipped with a front axle suspension, which is often designed as a hydropneumatic suspension [1]. Only few exceptions exist, such as the JCB Fasttrac, the Unimog, or self propelled sprayers, which are equipped with a full suspension. With a full suspension however, vibrations affecting the driver are reduced to a minimum.

Based on the following work, the hydropneumatic suspension and the control system have been developed further and were subsequently tested for their function, using reproducible driving tests. The different parameters and their effect on the road performance will be explained afterwards.

Tests, comparing different tractor suspensions carried out by Scarlett, Price and Stayner have shown a minimal acceleration amplitude for a fully suspended vehicle [2]. As for optimal driving safety a stiff spring and high damping is needed, while improved driving comfort can be achieved through a soft spring and low damping, a predictable and precise adjustment of spring and damper values has to be realized. This ensures that the driver always has full control over the vehicle and that wrong spring damper values cannot cause critical driving situations [3].

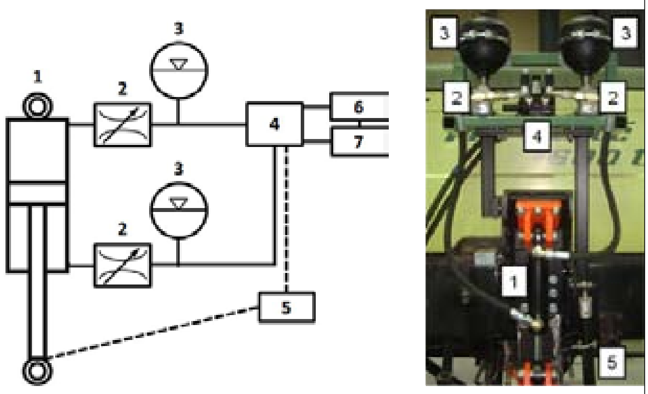
To realize this, new actors have been developed. Different investigations show the advantages of an active suspension over a conventional system. Schäfer shows that driving safety with long wave sine stimulation can be considerably increased [4]. Using switching 2/2 way valves testing the effects of an on/off Skyhook algorithm, Sarami demonstrates the superiority of an active suspension over a passive one [5]. Results on the hydraulic suspension test rig show a considerable increase of driving comfort [5].

Setup of the suspension system

The TU Berlin Trac, a modified system tractor based on a MB-Trac 1600 Turbo, was used as a test vehicle. During the design process of the front and rear suspension, as many original parts as possible have been used. Springs and dampers have been replaced by hydraulic cylinders, which have also been used at the modified rear axle by Hoppe [6]. The control of the rear axle in the horizontal direction is realized through longitudinal and transversal control arms.

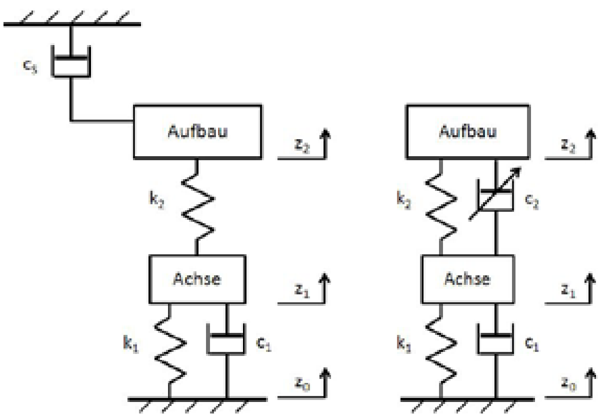
Figure 1 shows the structure of the hydropneumatic suspension. Piston and rod side of the cylinders (1) are connected to an accumulator (3). The spring force is realized through the gas pressure of this accumulator. Between both components a proportional valve (2) is placed. By adjusting its throttle cross section, the damping can be adapted according to the current driving situation. In this work, only the influence of the semi-

Fig. 1



Installed hydropneumatic suspension system

Fig. 2



Theoretical and practical skyhook concept

active suspension on the driving performance was measured, and therefore, no seat or cabin suspension was installed.

Control system setup

The control algorithm which is based on the Skyhook algorithm is optimized for maximal driving comfort. In this ideal concept, a passive damper between chassis and sky dissipates the energy that is induced by the unevenness of the underground **(Figure 2, left)**. That way, the chassis is decoupled from the underground, and the oscillation load is reduced. In practice however, an adjustable semi-active damper is used which controls the displacement of the chassis by adjusting the damping **(Figure 2, right)**. The described system uses a continuous adjustment of the throttle cross section of the proportional valves between cylinder and accumulator.

To determine the acceleration values which were used to assess the driving performance, a sensor was placed next to each wheel on the axle, and above each wheel on the chassis. Due to the fact that the velocity values that were necessary for the control strategy are hard to measure directly, the measured acceleration values were integrated by the software. Analog input modules containing A/D converters were used to acquire the signals. The signals were transmitted to a digital I/O card, where a logic connection between the different input and output ports was configured by software (FPGA – Field Programmable Gate Array). Using the algorithm implemented on the controller, in form of a Realtime-Labview-Model, the adjustment of the proportional valves was conducted. The allowed maximal and minimal damping rate was monitored by the software.

Tested parameters

The driving tests to evaluate driving safety and comfort were conducted on the site of the Wehrtechnische Dienststelle in Trier, Germany. The chosen "swiss track" (Schweizerbahn) has been designed according to ISO 8608 as a stochastic profile, with different stimulations for the left and right vehicle side [7]. The concrete track is 250m long and represents a dirt road or easy terrain. The unevenness for each vehicle side was created by chance, has no repetitions, and both sides do not influence each other. Therefore, the vehicle was not only excited to heave and pitch motion, but also roll motion.

Table 1

Tested parameters

Reifendruck ***Tire pressure***	**Konstant (1,4 bar vorne/1,6 bar hinten)** ***Constant (1.4 bar front/1.6 bar rear)***		
Fahrgeschwindigkeit *Driving speed*	7 km/h	11 km/h	14 km/h
Gefederte Achsen *Sprung axles*	keine Achse *none*	Vorderachse *front axle*	beide Achsen *both axles*
Ringseitiger Vorspanndruck *Rod side preload pressure*	63,7 bar (vorne/*front*) 69,8 bar (hinten/*rear*)	55 bar (vorne/*front*) 60 bar (hinten/*rear*)	80 bar (vorne/*front*) 85 bar (hinten/*rear*)
Passive Dämpfung *Passive damping*	minimal *minimal*	angepasst *adapted*	maximal *maximal*
Skyhook-Algorithmus *Skyhook algorithm*	on *off*	kontinuierlich *continious*	angepasst *adapted*

To assess driving performance at different situations, parameters were varied, and their influence on driving safety and comfort was examined **(Table 1)**.

Results

The influence of the chosen parameters on the driving comfort will be presented in the following section. To determine the driving comfort, accelerations at the seat of the vehicle were measured in the direction of travel (x), transversely to the direction of travel (y), and in the vertical direction (z). Subsequently, the root mean square (RMS) was calculated. **Figures 3 to 5** show the results for the z-direction and the RMS off all three directions.

Influence of driving speed

The influence of the driving speed was measured at 7 km/h, 11 km/h, and 14 km/h, on the swiss track. The suspension was set to the passive mode, so the proportional valves had a constant throttle cross section during the test. **Figure 3** shows that the RMS-value of the seat acceleration directly depends on the driving speed. A doubling of the speed results in nearly doubled acceleration values. To maintain the maximal allowed driver exposition values [8], the maximal speed has to be reduced.

Comparison of front and full suspension

Current tractors are, next to the cabin and seat suspension, often only equipped with a front axle suspension, to reduce chassis oscillations and to ensure sufficient ground contact. A full suspension however has a considerable advantage compared to front axle only suspensions, as can be seen in **Figure 4**. Accelerations in the vertical (z) direction can be reduced by 43 % using a full suspension. Furthermore, a full suspension assures that the rear wheels do not lose ground contact during critical driving maneuvers.

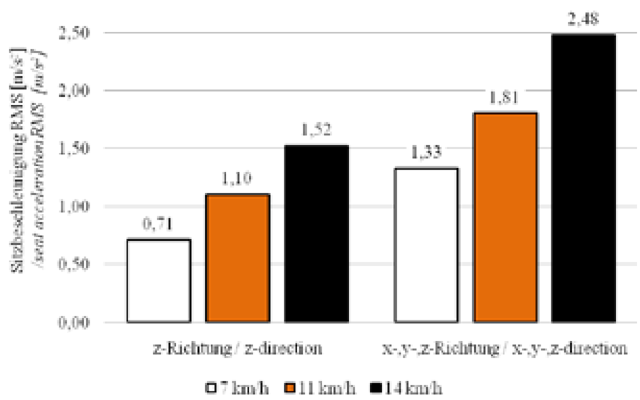
Comparison of semi-active and passive suspension

As can be seen in **Figure 5**, the vertical acceleration at the driver's seat was reduced by 8 % by the semi-active suspension. The vehicle's roll and pitch motion, which were not actively influenced in the current version of the suspension management system, resulted in a RMS-value of the three directions that did not reflect a decrease of accelerations. Improvements of the sensors as well as of the control strategy have the potential to reduce seat accelerations further. To reach this goal, roll and pitch motions have to be measured and influenced directly.

Conclusion

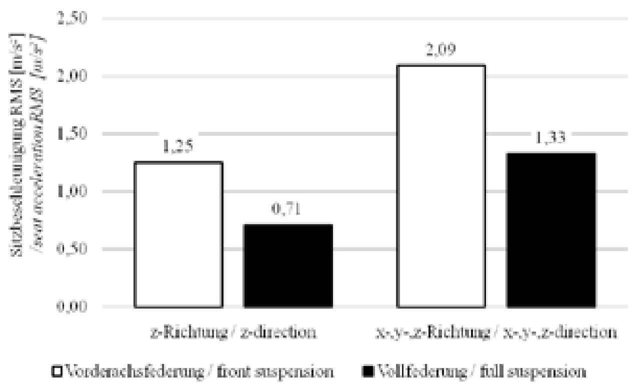
Using the hydropneumatic fully suspended test vehicle of the TU Berlin, a large variety of suspension concepts as well as parameters that influence driving comfort, can be examined. The presented results show that at high driving speeds, as they occur during transport, conventional suspension concepts reach their limit. Furthermore, the advantages that can be achieved with a fully suspended vehicle, regarding driving comfort, are evident. Intelligent control concepts can help to improve driving comfort. To use the full potential of the semi-active suspension and increase driving comfort as well as driving safety further research will be done at the TU Berlin.

Fig. 3



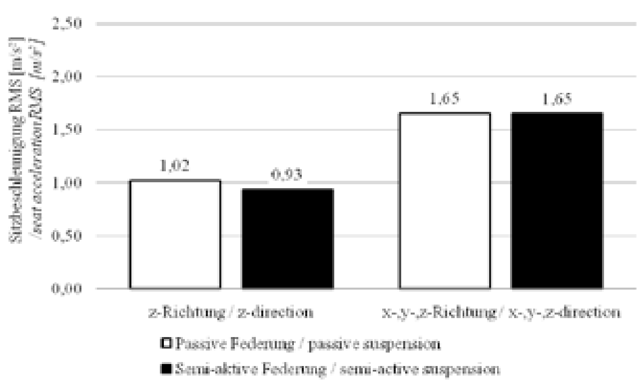
Seat accelerations at different speeds

Fig. 4



Seat accelerations with front and full suspension

Fig. 5



Seat accelerations with passive and semi-active suspension

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