ELECTRO-HYDRAULIC DAMPING STRATEGIES FOR HYDRO-PNEUMATIC SUSPENSIONS

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ABSTRACT

Operators of mobile machines are exposed to high vibration loads while on the machine. To reduce this, seat, cab, axle and wheel suspension systems are used today. In addition to a uniform ground pressure required to steer and brake the machines safely, the main aim is to reduce whole-body vibrations. The driving comfort can be improved and component stress can be reduced. The wide range of applications for such machines means that the suspension systems have to meet special requirements in various driving and working conditions. Due to characteristics suitable for mobile machinery, hydro-pneumatic suspension systems are increasingly being used in such machines. Adjusting the damping - either adaptively, semi-actively or actively - is one way to react quickly to changing conditions. This paper will focus on presenting and evaluating different damping strategies for hydro-pneumatics suspension systems. After a general overview of hydro-pneumatic suspension systems, the various damping strategies are discussed in detail. The effects of three damping strategies are explained in detail using the example of a tractor cab suspension.

Keywords: hydro-pneumatic suspension, damping strategies, mobile machine, tractor cab

1. INTRODUCTION

As long as mobile machines are not fully automated, operator comfort will remain one important requirement for those machines. In modern agricultural tractors, for example, the cab has become more than just the place for the driver to sit – nowadays, it is a workplace for many hours a day, especially during peak working seasons. In addition to comfort and efficiency, safety at work, thus the protection of operators' health, has gained importance. Diverse standards and regulations determine the dose of vibration to which a driver may be exposed within a certain period of time and how this dose can be measured [1].

In addition to driving comfort, controllability and tire-to-ground contact are also important. To ensure this, machine manufacturers are continuously improving their machines with active seats, suspended axles or wheels and specially designed cab suspensions.

2. STATE OF THE ART

The basic function of a suspension system is to isolate certain parts of a machine (usually the chassis), or the operator him- or herself from vibrations from the ground. The frequency range of suspension systems is below 25 Hz. In the case of vehicle dynamics, "operator comfort" is related to only this part of the frequency range [2]. With suspension systems, stress for driver and components can be reduced. ISO2631-1 [3] lists several diseases caused by vibrations on the human body – for example, excitations in the frequency range of 0.5 Hz to 0.75 Hz can be responsible for motion sickness.

As a result, suspension systems are used in a wide range of mobile applications. While mechanical spring and damper systems (see **Figure 1**, left) are typically used in passenger cars because of their simple design and low load changes, pneumatic systems are used in commercial vehicles. In these applications, additional features, e.g. lowering the chassis of buses for a better entry of passengers, are requested. Hydro-pneumatic systems (see **Figure 1**, right) are widely used in mobile machines. Here, especially the rough conditions and the higher load changes are main drivers for this technology. In contrast to pneumatic suspensions, hydro-pneumatic systems have separated media (oil and gas), which allows hydro-pneumatic suspensions to be blocked easily.

The main difference between mechanical springs and (hydro-)pneumatic springs is the progression of the spring rate. Mechanical springs usually have a linear characteristic (progressive or degressive is also possible). Pneumatic and hydro-pneumatic springs typically show a progressive behavior, which leads to a higher spring rate when the load is increasing and vice versa. In this way, the suspension characteristics are adapted automatically to the axle load. Depending on the layout, an approximation to a linear curve is possible with these systems, as well.

Apart from the main advantage of adapting the spring rate to the load, hydro-pneumatic suspensions are also beneficial when [4]:

- the level control has to deal with high load changes
- the suspension needs to be blocked
- the level control needs to react frequently and quickly
- the spring rate should be adjustable
- a compact and robust design is required

Tractors often have hydro-pneumatic suspension systems for front axles and cabs. Therefore, this type of machine is used as the reference application in this publication but should generally be seen as one of many mobile machines.

2.1 Hydro-pneumatic suspension systems

The suspension effect of hydro-pneumatic springs is mainly generated by the compressibility of the gas inside the accumulator. The compressibility of the hydraulic fluid (~1,2 % @ 200 bar [5]) and the elasticity of the hydraulic hoses only contribute a negligible amount. The spring rate is determined by the size of the accumulator, its precharge pressure and the load on the suspension system. Because of the wide load change of mobile machines, it makes sense to adapt the spring rate according to the actual load condition. In combination with higher spring rates, higher damping settings can increase comfort. For the front axle of tractors, the load can change depending on the work being done. A plow on the rear hitch reduces the front axle load, while a loaded front loader increases it. By using a differential cylinder, the spring rate can be influenced by a preload pressure in the rod side of this cylinder. Increasing the preload in the rod side leads to an increased spring rate of the suspension and vice versa [4].

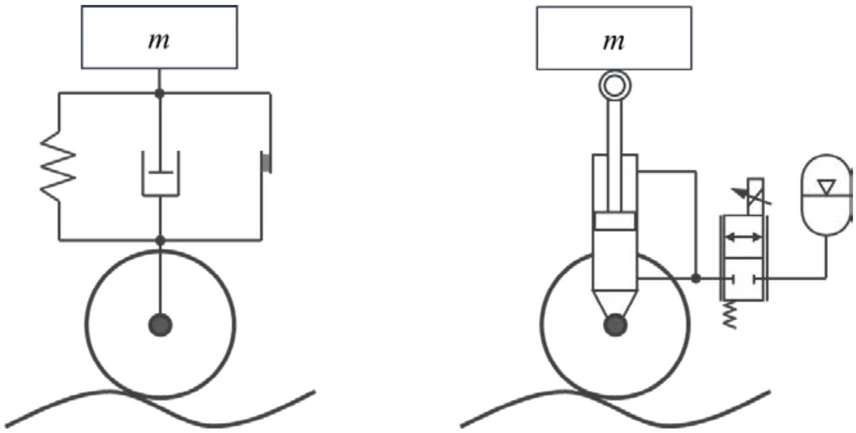

Figure 1: Mechanical (left) and hydro-pneumatic (right) suspension system

In addition to the suspension effect, unwanted damping in a hydro-pneumatic suspension can be caused by the following:

- solid friction in seals and bearings and
- viscous friction in tubes and pipes.

Friction causes a pressure difference that acts upon the active area of the cylinder, creating a retarding force. The viscous friction in tubes and lines should be kept rather low. However, under certain conditions it is helpful to generate additional damping. This is done by adding a flow restrictor between the cylinder chamber and the accumulator. An adjustable flow restrictor, like a variable orifice or an electronically controlled proportional valve, allows damping settings to be adjusted to the driving and working conditions.

Another core function of hydro-pneumatic suspensions is level control. Sensors detect a deviation of the suspension position, e.g. after a load change. An ECU is controlling a valve to reposition the suspension cylinder – see **Figure 2**.

This article focuses primarily on the various damping strategies. Detailed information on level control and adjusting the spring stiffness of hydro-pneumatic suspension systems can be found in [6] and [7].

2.2 Damping strategies for hydro-pneumatic suspension systems

The damping strategies for suspension systems can be classified into four different categories:

- passive systems
- adaptive systems
- semi-active systems
- fully-active systems

Passive systems are characterized by constant spring stiffness and fixed dampers. A soft spring rate and low damper settings offer a good body isolation, while a stiff spring rate and firm damper settings create good controllability on the machine body motion. Due to that fact, the behavior of passive systems is always a compromise between riding comfort and machine stability. Especially when there is a higher load change, these systems are designed to be rather rigid, creating performance losses in comfort.

Adaptive systems were developed to overcome these challenges. Depending on the working or driving conditions – e.g. driving on an even road vs. driving in the field – the damping settings can be adapted.

The easiest way is if the operator adjusts the settings himself. Usually, the operator can select between a soft, medium and stiff setup. In certain situations, the operator can even block the suspension. An advantage of adaptive systems is that the operator can adjust the damping settings according to his wishes; however, it is not possible to adjust properly to temporary changes. More advanced adaptive systems use electronic controls to switch the suspension characteristics automatically based on sensory information. Since only steady state changes (e.g. rough terrain vs. smooth terrain) are considered, low bandwidth controllers are sufficient.

Beyond that, ***semi-active systems*** react even to temporary changes, adjusting the damper setting more dynamically. By using adjustable dampers, the rate of energy dissipation can be influenced depending on the suspension motion. Aside from the more dynamic damper adjustments, the closed loop control of these settings is the main difference to adaptive approaches. The actively controlled forces in a semi-active system are only created by the damper, hence they only act against the direction of the suspension motion. The most popular semi-active suspension approaches are skyhook control and relative control. While dampers in conventional spring-damper systems reduce the relative speed between the isolated mass and the excitation, these more sophisticated solutions reduce the absolute speed of the suspended mass, thus its acceleration. With these approaches, a better combination of resonance damping and high-frequency isolation and consequently a more direct and quick reaction can be achieved. However, this is offset by higher costs for faster processors and components, as well as additional sensors that may be required.

In ***fully active systems,*** spring and damper are displaced by a force actuator. This actuator is placed directly between sprung mass and unsprung mass of the machine. The force actuator also allows to feed energy into the system independent of the direction of the suspension movement. To do so, special control algorithms are used, which energize the force actuator based on sensory feedback. The full bandwidth of the system provides good driving comfort and, at the same time, good controllability. In addition to the full bandwidth, they have a high-power consumption. This is a big disadvantage of these systems, especially against the backdrop of machine electrification. On top of this issue, the complex design makes this solution expensive, as well. Because of these reasons, fully active systems are only used in special applications.

A combination of different approaches can be used for the final application. One example is shown in **chapter 3** for a tractor cab suspension.

3. EXEMPLARY APPLICATION: TRACTOR CAB SUSPENSION

Nearly every manually driven mobile machine has an operator’s cab. This is why cab suspensions offer good opportunities to improve comfort. Since tractors are very versatile machines, they are used in a wide range of operating conditions: from working scenarios on the farm, driving on flat roads to working in rough terrain on the field. On the road, tractors are often used to transport implements to/from the field or to transport agricultural goods with a trailer. The driving speed is rather high, the controllability and the driving stability are more important than comfort. Thus, the cab suspension should be rather stiff. When driving in the field for hours with lower speeds, comfort and reduction of transmitted whole-body vibration are most important. For this type of work, the cab suspension should be set to a soft setting. This could be achieved with so-called adaptive damping: the operator selects between driving on the road or in the field. The damping setting is then switching between low and high, making the suspension feel soft or stiff. But to relieve the driver, solutions are shown that react automatically (semi-actively) to different driving conditions, without the need of the operator to interfere.

Figure 2 shows an exemplary cab suspension of a tractor and the hydraulic design. The hydraulic manifold contains the proportional damping valve (no. 3), as well as two valves for leveling the suspension (no. 1 and no. 2). The cab can be lifted by activating valve no. 1. If the cab is supposed to be lowered, valve no. 2 needs to be opened. The damping can be proportionally adjusted by valve no. 3. There is also a small bypass orifice in parallel to protect the suspension from pressure peaks if the damping valve is completely closed. In order to guarantee the best possible body isolation, the cab suspension is typically laid out rather soft. In this case, this means a basic damping setting of 55 % (55 % is the percentage ratio between min. and max. valve opening). The soft suspension typically has a long suspension travel, which can lead to tricky situations in some driving and working conditions: excitations close to the natural frequency, heavy bumps, etc. Different concepts from chapter 2.2 are therefore combined to set up a sufficient suspension system.

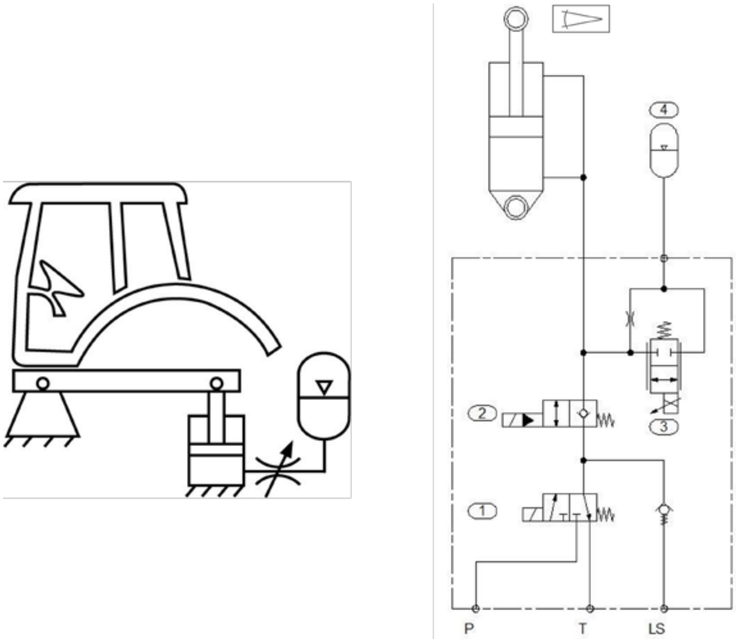

Figure 2: Cab suspension of a tractor

3.1 Relative control

To better adapt the performance of the suspension to the existing vibration conditions, the relative control approach can be used. The relative control is a modification of the skyhook control approach. To generate the connection of the suspended mass to the sky – “the hook” – the skyhook control uses an acceleration sensor. Additionally, the relative speed between unsuspended and suspended mass is measured by a second sensor. This makes the skyhook control quite complex and expensive. The relative control only needs the existing position sensor already installed for level control of the suspension. This makes this solution much more cost-effective.

Similar to the skyhook control, the approach behind the relative control [8] is to use the damping forces whenever they are beneficial to reduce the acceleration of the suspended mass. The relative control therefore optimizes comfort by reducing these accelerations. It can be used as an extension to the standard damping and applies only at high speeds.

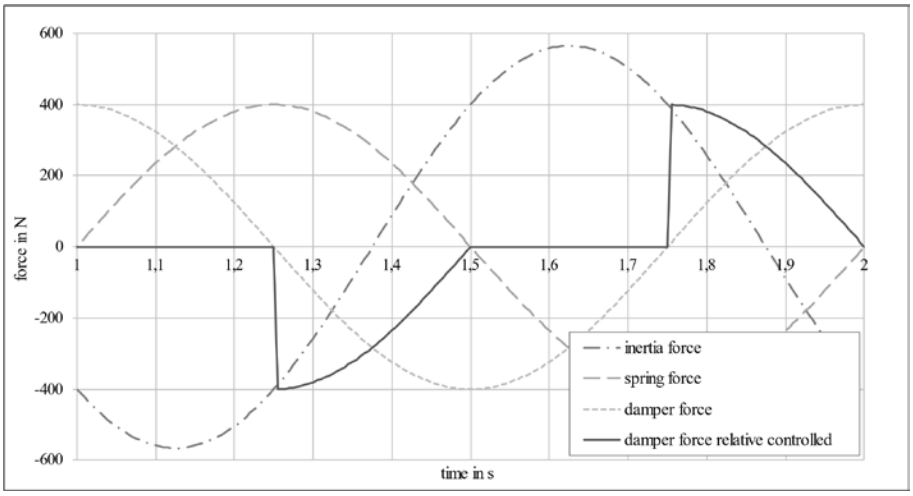

Figure 3: Relative controlled damping force in a vibration isolator based on [8]

Figure 3 shows the oscillation force curve of a passive oscillation isolator (see **Figure 1** left). In addition to the force of inertia, the spring and damper forces are shown. In certain time periods of the oscillation, the dampers´ force and the spring force have equal directions. In other periods the direction of action is different.

Because the inertia force F_I ($F_\mathrm{I} = m \cdot \ddot{x}$) of the mass corresponds to the sum of spring ($F_\mathrm{S} \sim x$) and damper force ($F_\mathrm{D} \sim \dot{x}$), the following equations explain the context:

$$|\ddot{x}| = \frac{|F_S| + |F_D|}{m}, t \in \left[t_0;\ t_0 + \frac{T}{4}\right] \cap \left[t_0 + \frac{T}{2};\ t_0 + \frac{3T}{4}\right] \quad (1)$$

$$|\ddot{x}| = \frac{|F_S| - |F_D|}{m}, t \in \left[t_0 + \frac{T}{4};\ t_0 + \frac{T}{2}\right] \cap \left[t_0 + \frac{3T}{4};\ t_0 + T\right] \quad (2)$$

Because the acceleration of the mass, thus the force of inertia, corresponds to the sum of spring and damper force, the damping force reduces the acceleration of the mass in certain sections and amplifies it in others. When focusing on equation (2), it can be seen that the damping force reduces the acceleration of the mass in the time frame for which the equation is defined. Because of this, the damping forces must only be applied to the mass in the appropriate time frames in order to reduce its acceleration. This leads to an on-off control of the damper. Because the spring force is not constant, the damping force should be continuously adjustable in accordance with the current spring force to optimize this approach [8]. **Figure 4** shows the continuous damping adjustments for the position curve of a cab suspension when driving on a dirt track with 20 kph with the relative control algorithm. The static stroke position of the suspension is 50 %. The static damping is unchanged at 55 %. The relative damping is added at the desired conditions, see equation (2).

As the correlation between spring force and compression of a hydro-pneumatic spring depends mostly on the system design (accumulator size, precharge pressure, etc.) and is often nonlinear – the system could further be optimized by taking this into consideration. This would help to better adapt the damping forces to the actual spring forces.

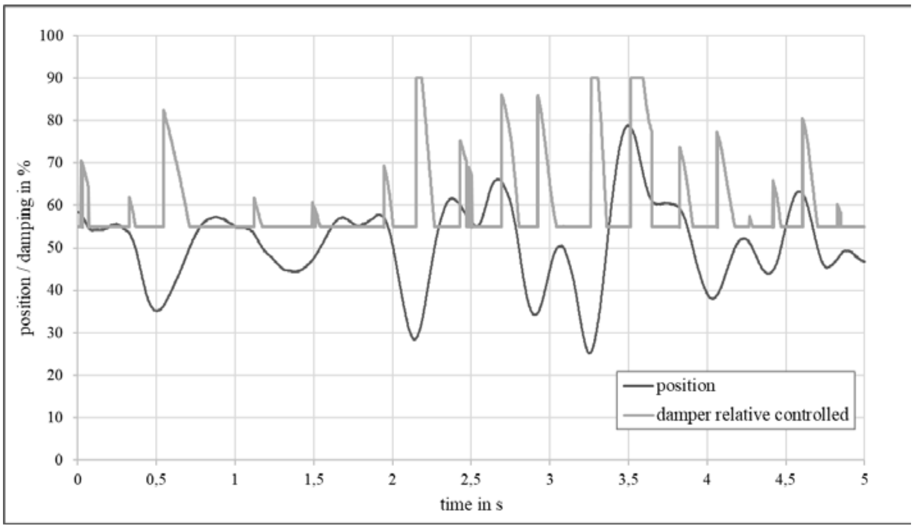

Figure 4: Damping setting relative controlled

3.2 End-Stroke-Damping

The wide range of usage of a tractor can cause situations in which a soft laid out suspension can get to its limits. High force peaks coming from the chassis, e.g. when driving over a bump or a pothole, can deflect the suspension cylinder in a soft suspension to its end stop, resulting in increased component stress or even damage to the system. Furthermore, in such situations, the forces are transferred more or less directly into the cab, which may cause injuries of the driver or loss of machine control. There are cylinders with end stop damping available, but incorporating these means extra costs for each machine. Moreover, if a damping valve is already available in the suspension circuit, it can be used for a software-based end stop damping.

Whether end-stroke-damping – which causes a deceleration force of the piston – is activated depends on two system conditions:

- the position of the suspension cylinder: the closer the piston is to one of the two end stops, the higher the risk of reaching one of them. For the suspension, this means that the damping needs to be increased, the closer the piston gets to one of the end stops.
- the speed in the direction of an end stop: the higher the speed, the more kinetic energy is stored in the system. Assuming a certain position outside the middle stroke position, higher energy means higher risk of reaching the end stop. Therefore, more damping is necessary to reduce this risk by reducing the speed.

These two conditions need to be carefully harmonized so that the damping only intervenes when necessary. Otherwise, the suspension could become too stiff under normal driving conditions, or even worse, a hydraulic end stop could occur: If the damping valve is closed too much, the oil cannot flow into the accumulator, causing a high pressure peak in front of the spool lands. Instead of hitting the mechanical end stop, the piston would hit a “hydraulic” end stop.

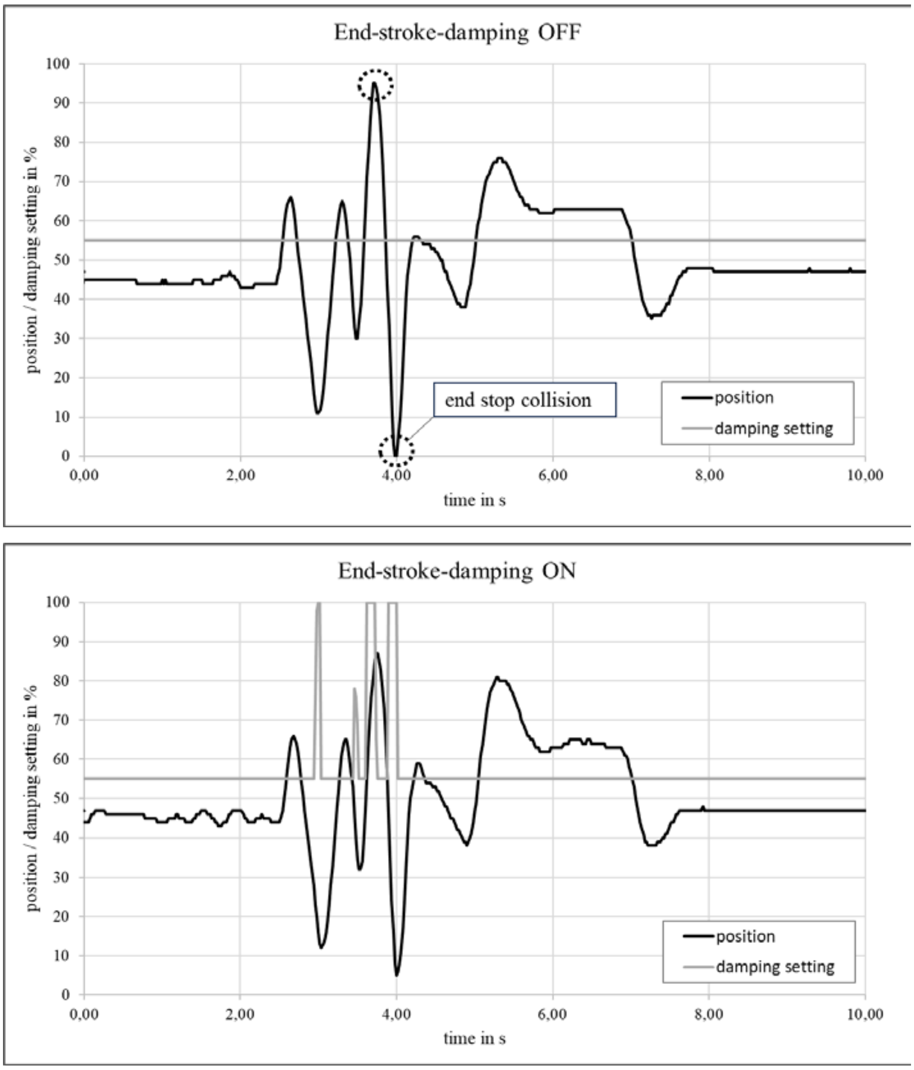

Figure 5: stroke position w/o end-stroke-damping

To explain how the damping strategy works, a test run was carried out - driving over an obstacle (height: 80 mm, length: 1200 mm) with 12 kph, see **Figure 5**. In the diagrams, the first excitations (see time at 3 s) come from the front axle, which reached the obstacle first. When the rear axle moved over the obstacle (see time at 4 s), the excitations for the cab suspension were even higher. The activated position control compensated for long-lasting deviations from the target position. This had no effect on the large oscillations, but an effect can be seen at the end of the test run.

The upper diagram shows the stroke position (black line) with the end-stroke-damping shut off. Again, a constant damping setting of 55 % was applied to the suspension. The spring system showed a relatively soft behavior, as desired. When the rear axle passed over the obstacle, the lower end stop was reached and there was a hard impact inside the cab.

The lower diagram shows the influence of the activated end-stroke-damping. The constant damping is set to 55 %, as well. With end-stroke-damping, the damping was increased, temporarily and only when necessary, to prevent end stop collision.

3.3 Harmonic Oscillation Damping

Road and driving conditions occasion the suspension systems of a mobile machine to oscillate to a greater or lesser extent. If the frequencies of the excitations are close to the natural frequency of the suspension the oscillations are superimposed. Sometimes these oscillations last for a longer period of time (e.g. if the road conditions do not change), which leads to a very unpleasant condition for the operator and could cause so-called seasickness.

To get rid of these disruptive oscillations, energy needs to be extracted with the damping valve. The harmonic oscillation damping approach detects oscillations within a certain frequency spectrum by using the position sensor signal. If these oscillations do not subside after a certain period of time, the damping setting is increased step by step, until the oscillation energy is reduced to such an extent that the continuous oscillations disappear or are reduced to a tolerable level. Damping setting will then be decreased. If the oscillations start intensifying again, the damping is increased again, as well. The advantage of this approach is that the suspension is only stiff when needed, thus achieving good decoupling under regular operating conditions.

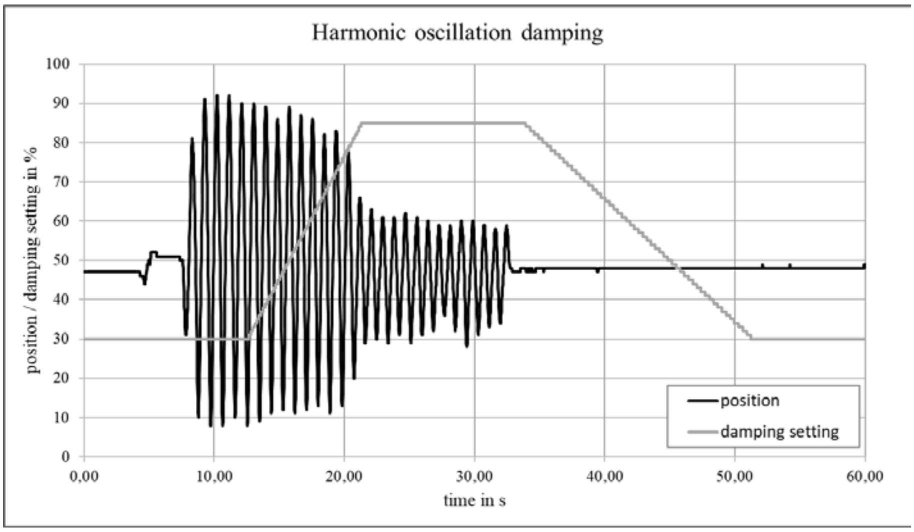

Figure 6: Oscillation reduction with harmonic oscillation damping

The diagram in **Figure 6** shows the impact of the harmonic oscillation damping. To better see the impact of the harmonic oscillation damping, the suspension was artificially deflected with a high amplitude. This was done by rhythmic acceleration of the tractor with the gas pedal. Even with excitations up to 30 s, the increasing damping setting reduced the oscillations, resulting in less movement. After the excitations stopped and the suspension movement came to a rest, the harmonic oscillation damping control reduced the damping settings to the lower level, in this case 30 % again. Depending on the setting of the gradient, the damping makes the suspension more or less rigid.

4. CONCLUSIONS

Mobile machines have a wide range of applications. This is why their suspension systems must meet a variety of requirements. The adjustability of the damping settings of a hydro-pneumatic suspension via software offers a great opportunity for individual solutions that are tailored to different operating conditions. There are numerous approaches to optimize the suspension performance.

The measurements for a tractor cab suspension showed that with end-stroke-damping and harmonic oscillation damping, there are two control strategies, which can increase the comfort in special operating conditions. At the same time, component stress can actively be prevented, extending the service life of the machine and particularly the suspension parts. The relative control can be used without having to implement complex and expensive additional equipment. Further optimization steps could be done regarding the time response of the damping valve in order to generate better timed forces. Furthermore, the nonlinear spring curve of the hydro-pneumatic spring could be taken into account to further optimize the damping forces according to the theory.

NOMENCLATURE

F_D	Damper force	N
F_I	Inertia force	N
F_S	Spring force	N
m	Mass	kg
t	Time	s
t_0	Start time	s
T	Periodic duration	s
x	Movement	m
$\dot{x}$	Speed	m/s
$\ddot{x}$	Acceleration	m/s²

REFERENCES

[1] ISO 10326:2002-07 Traktoren und Landmaschinen auf Rädern – Messung der Ganzkörperschwingungen, 1st edition. ISO, Switzerland

[2] Sarami S (2009) Development and Evaluation of a Semi-active Suspension System for Full Suspension Tractors, page 8. TU Berlin, Berlin, Germany

[3] ISO2631-1:1997-05 Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration, 2nd edition. ISO, Switzerland

[4] Bauer W (2008) Hydropneumatische Federungssysteme, 1st edition. Springer, Berlin

[5] Findeisen D (2006) Ölhydraulik – Handbuch für die hydrostatische Leistungsübertragung in der Fluidtechnik, 5th edition. Springer, Berlin

[6] Bauer W (2014) 9th International Fluid Power Conference. Aachen, March 24-26, 2014, Aachen, Germany

[7] Antoni S (2022) 13th International Fluid Power Conference. Aachen, June 13-15, 2022, Aachen, Germany

[8] Hauck M (2001) Geregelte Dämpfung für Traktor-Fahrersitze, page 57-59. TU Berlin, Berlin, Germany