Performance of an electro-hydraulic active steering system

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Abstract
Hydrostatic steering systems are used in construction and agricultural machines alike. Because of their high power density, hydraulic drives are qualified for the use in vehicles with high steering loads. Conventional hydrostatic steering systems are limited in terms of steering comfort and driver assistance. For realisation of appropriate steering functions, electro-hydraulic solutions are necessary. This paper provides an overview on existing implementations and introduces a novel steering system. The presented active steering system with independent meter-in and meter-out valves fills the gap between existing active steering systems and steer-by-wire solutions. An appropriate control and safety concept provides advanced steering functions for on-road usage without the fully redundant structure of steer-by-wire systems.

KEYWORDS: active steering system, steering function, functional safety, test vehicle

1. Overview and system introduction
Hydrostatic steering systems of various designs are used in construction and agricultural machines alike. The increasing complexity of workflows requires driver-assisted steering
or even an automation of steering-functions. Therefore electronically controlled components are necessary, which could be integrated to the steering system in several ways. Thereby two basic concepts of active steering systems may be identified: superimposed steering systems and pure steer-by-wire systems (see Table 1).

<table>
<thead>
<tr>
<th>principle</th>
<th>convention. steering</th>
<th>active steering system</th>
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<tbody>
<tr>
<td></td>
<td>LAG</td>
<td>superimposed steering system</td>
</tr>
<tr>
<td></td>
<td>(convent. steering unit)</td>
<td>LAG + el. motor</td>
</tr>
<tr>
<td>functionality</td>
<td>not electrical, no advanced steering functions</td>
<td>steering functions realisable</td>
</tr>
<tr>
<td>safety</td>
<td>road approval</td>
<td>fail silent</td>
</tr>
<tr>
<td>installation flexibility</td>
<td>limited</td>
<td>limited</td>
</tr>
</tbody>
</table>

Table 1: hydraulic steering systems in mobile machines

Superimposed steering systems still use a conventional steering unit (LAG). An additional hydraulic path superimposes a volume flow, thus a variable steering ratio is realised. Through the avoidance of the rigid ratio between steering wheel and steering cylinder, several comfort and assistance functions can be implemented. In case of failure, the superimposition can be separated from the steering system. The vehicle is
still manoeuvrable, through the conventional hydrostatic steering unit. Furthermore, the properties of emergency steering are preserved.

One possibility to realise a superimposed steering system is to mount a summation gearbox at the steering linkage. The rotational speed of the steering wheel and of an additional electric motor are added at the planetary gear. Therefore, the rotational speeds influence the conveyed volume flow of the steering unit. An electronic control unit (ECU), dependent on driver input and the implemented steering functions, controls the electric motor. Comparable implementations are applied in automotive industry /1/. In case the steering volume flow is to be superimposed instead of rotational speed, electrohydraulic proportional valves can be used in addition to the steering unit. The control of the valve is realised by means of different sensor signals. An available active steering system is the OSPE from Danfoss Power Solutions /2/. In case of on-road use, the electrohydraulic valve section must be deactivated, because failures in the electrohydraulic part cause safety-critical states and a time-critical deactivation is necessary. Then steering is possible using the conventional steering unit.

If the mechanical linkage between steering wheel and steering valve is completely eliminated, the system is called steer-by-wire system (SBW-system). This solution is done without a hydraulic-mechanical backup. An ECU processes the sensor data and generates actuating values. Two different structures can be found:

The first one is a displacement-controlled system comparable to /3/ or /4/. The second approach are valve-controlled steer-by-wire systems, based on electrohydraulic proportional valves. Such concepts are presented in /5/ or in /6/. For a roadworthy SBW-system an extensive safety concept and an entirely redundant structure is necessary to avoid a dangerous machine behaviour in case of failure. Steer-by-wire systems without redundancy are usually equipped with a superimposed, prioritised conventional hydrostatic steering unit. In case of high velocities and on-road use, the conventional system is activated. The utilisation of the electrohydraulic steering is permitted only at lower speeds. The structure layout corresponds to the superimposed steering system, but the hydrostatic and electrohydraulic steering are not active at the same time. There is no superposition of volume flow (/7/, /8/).

The proposed approach to implement an electrohydraulic active steering system is the realisation of a superposed valve structure with independent meter-in and meter-out valves (see Figure 1). One main advantage is use qualification for on-road applications without the entirely redundant implementation of SBW-systems. Appropriate valve control strategies open this opportunity, because it is possible to compensate single
failures inside the configuration and reduce their adverse effects. The valve structure consists of four separate 2/2 proportional way valves, which allow an extended control intervention. Through independent actuation, faulty states become tolerable in a wide operation range. Thus, the safety level is significantly increased. A time-critical deactivation is not necessary anymore. In accordance with conventional superimposed steering systems, the conventional steering unit is preserved. Due to the internal hydraulic-mechanical follow-up control of the steering unit, an oil flow is adjusted proportionally to the rotational speed of the steering wheel. In addition to an ECU, two angle sensors (steering wheel and wheel) are functionally necessary. By means of a permanent nominal-actual value comparison, the superimposed valve structure is controlled. Different steering functions are enabled through various set-point specifications. The electrohydraulic steering system can be deactivated through a switch valve. An additional switch valve allows for changing the operation mode between reaction and non-reaction behaviour.

**Figure 1:** system structure of the novel active steering system

### 2. Features of active steering system with independent metering

The increasing utilisation of active steering systems serves the realisation of various driver-assisting functions. Possible applications range from influencing the steering ratio, steering interventions for driving stability to fully automatic steering manoeuvres. The functional requirements of the novel superimposition steering system are limited to the
two aspects mentioned first. However, automatic steering functions can be realised as well with the introduced system. Precondition is the availability of appropriate sensor signals and corresponding control values.

The steering functions listed below are implemented:

- Directional stability and leakage compensation
- Variable steering ratio
- Defined centre position of steering wheel („12 o´clock position“)
- Ability to switch between reaction and non-reaction behaviour

In purely hydrostatic steering systems, high external loads result in a slight displacement of the steering cylinder due to leakage, although no steering is intended. This results in a continuous correction of the vehicle’s trajectory by the driver on inclined lanes. The implementation of a leakage compensation enables the directional stability of the machine.

In order to adjust the needed steering effort to different driving situations it is necessary to adapt the steering ratio. This is realised by means of several constant steering ratios for each driving range and mode or by a variable steering ratio, which continuously adapts to the driving state. The implemented variable steering ratio depends on the vehicle’s speed. Thus, a good directional stability at high velocities and comfortable handling for slow driving is possible.

In agricultural and construction machines, usually there is no defined neutral position of the steering wheel. This is due to the already mentioned leakage in conventional steering units or to a variable steering ratio depending on the driving state. Therefore, the steering wheel of such vehicles cannot be equipped with several control elements, as it is the case in commercial vehicles and passenger cars. An integration of various control elements would offer new possibilities in cabin design and increases the ease of operation.

By the use of fully automatic driving functions, the vehicle performs a defined steering motion without any driver-induced steering wheel rotation. During autonomous driving manoeuvres, there should be no noticeable reactions at the steering wheel. Therefore, a non-reaction behaviour of the conventional steering unit is required. Additionally, there is sometimes a demand for automotive driving experience. This includes noticeable steering forces at the steering wheel and wheels, which lead to automatic centring of the
wheels. To satisfy those opposing requirements a changeable operating state is necessary.

3. Development and realisation of the active steering system

The design, implementation and testing of the active steering system with independent valves and the implemented steering functions was conducted in a multi stage development process. In the first step, the novel steering system was analysed in a system simulation. The built simulation model based on (1) a complex, physical model of the steering system, (2) the machine periphery and (3) the surrounding process conditions. Due to the detailed modelling, verifiable and application-specific statements can be derived.

Besides the simulative considerations, a test rig was built at the IFD (Institute for Fluid Power Dresden). Realistic testing conditions are achieved by integrating the steering system into the actual hydraulic and mechanical machine periphery. Therefore, the whole steerable front axle of the vehicle and the hydraulic steering circuit were implemented at the test rig. Furthermore, an electro-hydraulic cylinder drive generates operating point dependent loads. Various calculation models and presets are available for a provided load set-point. The test rig’s control as well as the acquisition of measured data is done by an integral monitoring and control system. The test rig is shown in Figure 2.

![Figure 2: steering system test rig at the IFD](image-url)
Additionally to the test rig, the steering system was implemented into a demonstrator vehicle (Fendt 927 Vario) for testing the system and the steering functions under realistic operating conditions.

**Figure 3** shows the demonstrator driving straight ahead under permanent exposure to an external load. This load state appears while driving on inclined lanes or under operating conditions with inhomogeneous wheel load distribution. As the measurement shows, a continuous steering motion is necessary to keep the vehicle on track. If the leakage compensation for directional stability is activated, the operator intervention can be omitted. The cylinder directly follows the demand of the driver, because of the steering wheel- and wheel-dependent control of the superimposed steering system. The cylinder drive is working in a closed loop manner.

<table>
<thead>
<tr>
<th>Steering system without directional stability</th>
<th>Steering system with directional stability</th>
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<td><img src="image" alt="Diagram" /></td>
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**Figure 3**: vehicle measurement with deactivated and activated directional stability

To additionally increase driving comfort, a steering ratio depending on the vehicle speed is implemented. This variable steering ratio usually results in different steering effort for steering motions in an arbitrary driving cycle. Accordingly, the neutral position of the steering wheel is manipulated. The system characteristics with activated and deactivated “12 o’clock position”-function are compared in **Figure 4**. An exemplary test track is driven. A steering manoeuvre at the beginning of the measurement causes the loss of steering wheel’s centre position. In this initial state the angle of the steering wheel $\phi_{sw}$ is 200° at centred wheels ($\phi_w = 0°$). Without activated steering function, which adjusts the defined neutral position, this deviation changes depending on the driving state. This may
lead to a reduction or an enlargement of angular deviation. The position of the steering wheel seems random. For passing through the test track with the activated “12 o’clock position”-function an initial deviation is provided ($\varphi_{sw}(\varphi_w = 0^\circ) \approx 200^\circ$), similar to the test with deactivated function. As shown in Figure 4, the implemented steering function reduces the angular deviation and the steering wheel tends toward its centre position. To provide this feature, the steering ratio is slightly adapted. This change is not noticeable by the operator.

**Figure 4:** Steering without (left) and with defined neutral position of steering wheel (right) – “12 o’clock position”

### 4. Safety concept

To fulfil all legal requirements as well as the operator’s expectations of safety and availability, an integral safety concept corresponding to DIN EN 13849 /9/ and ISO 25119 /10/ is developed. Based on risk assessment, possible hazards are evaluated and a required performance level is identified. The definition of appropriate safety
functions serves the reduction of emerging risks by maintaining a safe state or by taking measures to pass over to a safe state in case of failure. Because mobile machines are operator-controlled and their operating scenarios are subject to significant variations, there are many safety-relevant operational states. A comprehensive failure simulation, adopted from the introduced simulation model, allows for the reproduction of all basic conditions. With failure simulation, it is possible to analyse possible failures and their effects on the entire steering system as well as vehicle behaviour. The simulation is comparable to an FMEA (failure mode and effect analysis) and helps to identify critical components relevant for the safety function. Notably, the electrical and electronical components of the steering system are in the focus of attention, because they cannot be designed fatigue endurable like mechanical parts and show a stochastic failure behaviour. Additionally valve and sensor errors are considered. In order to derive universal statements relating to failure effects, all relevant operating states like pulling and resistive loads are considered. Thus, there is a significant number of faulty system states.

With the help of a simulation-based identification of safety-critical components, a safety-related block diagram can be derived for the safety function. The block diagram illustrates the structural composition of the safety function and provides the basis for the calculation of the present safety level /11/.

For the development of safety concept of the steering system, a merely simulative consideration is insufficient. Especially for complex, safety relevant systems test rig trials and field tests are indispensable. Thus, it is necessary to investigate the system behaviour in case of a single failure at the test rig and at the demonstrator vehicle to validate the safety concept. The considered faulty states correspond to errors reviewed in the failure simulation. Testing the safety concept at the demonstrator represents the highest level of validation, because the outcome is not influenced by model-based simplifications or by limits related to the test rig. Faulty states are forced by the electronic control device. An excerpt of the executed error analysis is shown in Figure 5.

The figure illustrates the behaviour of a conventional and the novel superimposition steering system in a case of failure. In a conventional active steering system, an accidentally opened valve leads to a dangerous movement during straight ahead drive, because of a faulty volume flow to the steering cylinder. The driver is not able to compensate the failure effect ($\Delta x_{cy} \approx 150$ mm). The superimposed steering system must be switched off time-critically to preserve manoeuvrability. If a comparable single error occurs in a system with independent metering, safety critical states will not appear. By
the actuation of the remaining faultless valves, the effect of the failure is reduced ($\Delta x_{\text{cyl}} \approx 5$ mm). The operator maintains control over the vehicle and manoeuvrability is preserved. Measurements of the test rig and the demonstrator as well as the simulation results show comparable characteristics.

The validated safety concept shows that in case of error the harmful effect of a failure can be reduced or fully compensated. A time-critical deactivation of the superimposed steering system is not necessary, because an error does not cause any immediately negative effects. There is more time to detect a faulty state reliably. This improves availability of the system, because singular events do not lead to a deactivation of the active steering system. Simple methods of error detection can be applied such as monitoring of limit and trend values. Other approaches, for example model-based state observers, are not necessary.

5. Summary
This contribution describes the development and evaluation of an electro-hydraulic active steering system. It was verified that all functional and safety relevant requirements can be fulfilled by means of a valve structure with independent metering. A road approval
for the steering system is possible, because faulty states in the steering system do not affect the machines safety and the vehicle’s manoeuvrability is preserved. The introduced system reaches a high safety level without using a fully redundant structure. Thus, the system is able to close the gap between existing superimposed steering systems and steer-by-wire solutions. Based on extensive simulations and experimental evaluation, potentials and limits of the analysed concept can be shown.

6. Acknowledgement

The European Union supports this research and development project with funds from the European Regional Development Fund (ERDF).

7. References


8. Nomenclature

\( i_{\text{max}} \)  Maximum ratio  \\
\( i_{\text{min}} \)  Minimum ratio  \\
\( t \)  Time  \\
\( v_{\text{vehicle}} \)  Velocity of the vehicle km/h  \\
\( x_{\text{cyl}} \)  Position of the steering cylinder mm  \\
\( \Delta x_{\text{cyl}} \)  Displacement of the steering cylinder mm  \\
\( \varphi \)  Angle  \\
\( \varphi_{\text{sw}} \)  Angle of the steering wheel  \\
\( \varphi_{\text{w}} \)  Angle of the vehicle’s wheel  


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