Design and test of an intelligent energy efficient valve to decrease pressure pulsation in power steering systems

Torsten VERKOYEN, Hubertus MURRENHOFF

Abstract: In a joint research project BMW and IFAS analyzed two well known hydraulic phenomena occurring in power steering systems, in order to reduce noises, that are caused by these phenomena. The research project was subdivided into three tasks. The first task incorporated the analysis of the power steering system of a BMW 5 series passenger car. During this analysis an impulsive pressure pulsation phenomenon known as rattling as well as a periodic pressure oscillation called shuddering were measured. Both phenomena result in distracting noises within the passenger cabin and occur during certain different driving manoeuvres. The second task included the construction of two test benches to reproduce rattling and shuddering independent from the car. A comparison of the measured data obtained by driving tests with the collected data from the test benches verified their functionality and accuracy. Another advantage of the test rig is that it provides easy access to the power steering system's components. Modifications can therefore be carried out in a short amount of time. Finally an intelligent valve was designed and tested at the two test benches. The valve can detect the two different hydraulic phenomena without the need of sensor signals and without causing high pressure drops. In case of rattling the valve softens the return line of the power steering system and in case of shuddering the return line is hardened. A softer return line reduces pressure pulsations while a harder return line is insensitive to periodic pressure oscillations. This paper describes a solution for two different hydraulic phenomena (rattling and shuddering) occurring in power steering systems. The solution is the integration of an intelligent energy efficient valve into the power steering system's return line, which changes the stiffness of the return line depending on the occurring phenomenon without affecting the sensation of the steering. The functionality of the presented valve is proven by means of the test results obtained from two test rigs designed to reproduce the described phenomena.

Key words: Power Steering System, Rattling, Shuddering, Pressure Pulsation,

Introduction

The reduction of ambient noise has gained great importance in modern automobile design. Following the achievements which have been made in eliminating the engine as a major source of noise, the latest trend in development focuses on ancillary components with a high power density. Among these components, hydraulic power steering systems prove to be a particularly challenging example. The typical design of a hydraulic power steering system is shown in *Figure 1*.

The steering movements of the driver cause the torsion bar to induce a difference angle between valve input shaft and valve housing. This difference angle leads to twisting out the steering valve, which is designed as a hydraulic full-bridge, so that fluid enters from the pump trough the pressure line and steering valve into the respective cylinder chamber, causing overall movement of the steering cylinder.

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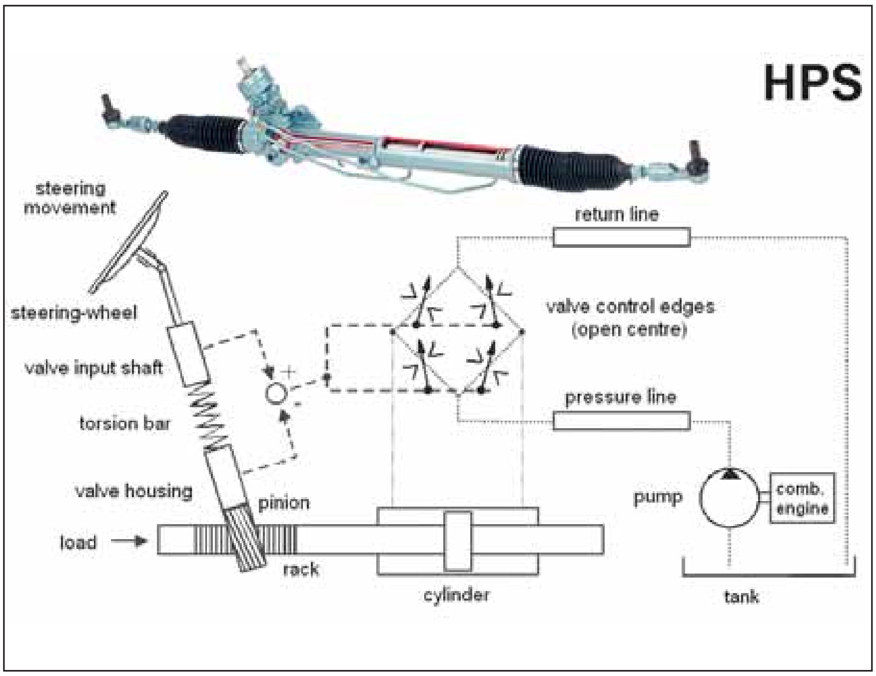

Figure 1. *Hydraulic Power Steering System*

The volumetric flow from the second cylinder chamber passes through steering valve and return line into the tank. The valve housing has a gear pinion attached to its end and is joined with the steering cylinder by means of a gear rack. Thus, the difference angle between valve input shaft and valve housing may be compensated by the axial movement of the steering cylinder. If at this point, an external load is applied to the gear rack however, the aforementioned mechanical joint between valve housing and steering cylinder can cause the valve to twist out, leading to increased pressure in the steering system. In this case the steering system is driven by the external load.

Well known accoustic phenomena in hydraulic power steering systems are rattling and shuddering. These are frequently misinterpreted by the driver as a malfunctioning of the steering system. Both accoustic phenomena, rattling as well as shuddering, are brought about by two different driving situations. Rattling, for instance, is caused by driving over an obstacle while moving the steering system at slow vehicle speeds (*Figure 2*).

In daily traffic, kerbstones or floor sills in car parks constitute the most common form of such obstacles.

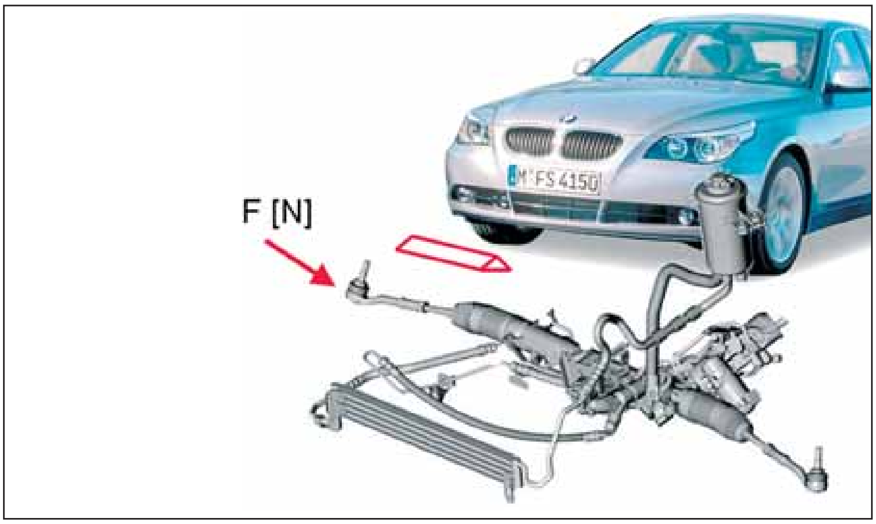

Figure 2. *Driving situation for rattling*

The sudden load induced on the undercarriage by driving over the obstacle is conducted via the steering link onto the steering cylinder.

In the steering system, this incitement of load causes pressure and volumetric flow pulsations, which result in the characteristic oscillating rattling noise.

The phenomenon of shuddering on the other hand, is caused by moving the steering system while the brake system is engaged and the vehicle is at a standstill (*Figure 3*).

Steering on smooth, painted car park floors can lead to a self induced stick-slip effect between tires and surface. As is the case during rattling, this incitement of load is transferred via the steering link onto the steering system. This means for the steering hydraulics, that shuddering causes pressure and volumetric flow pulsations, which are lower in frequency than those observed for the rattling phenomenon. However, next to the disturbing noise, shuddering can also be felt by the driver due to an oscil-

Figure 3. *Driving situation for shuddering*

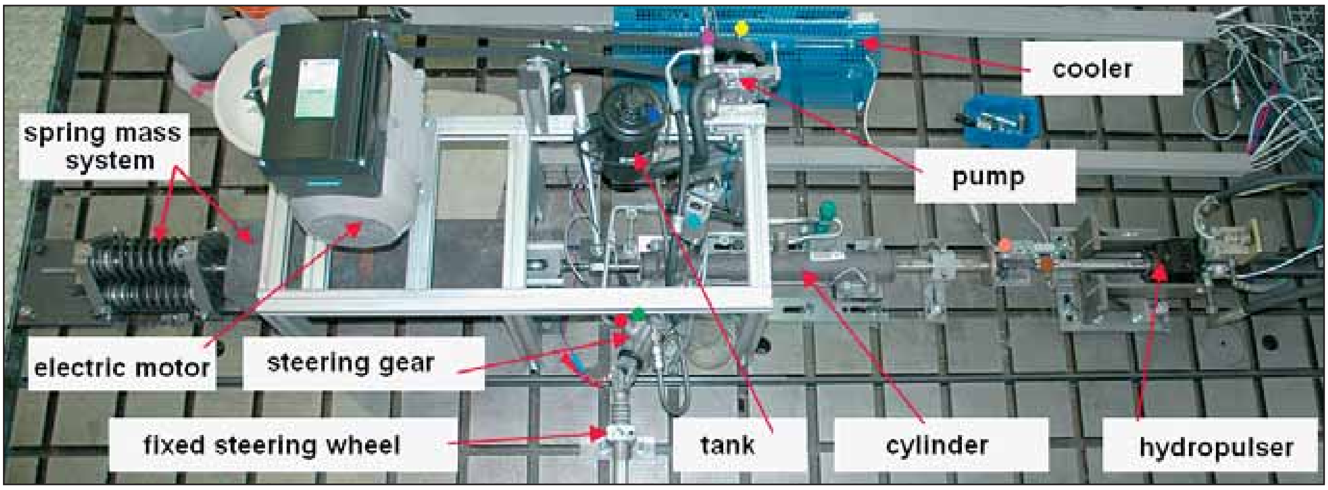

Figure 4. *Test bench for rattling*

lating torque acting on the steering wheel.

Analysis of the acoustic phenomena

In a joint research project conducted by BMW and IFAS, both accoustic phenomena were examined. One task consisted in the construction of adequate test benches, to reproduce rattling and shuddering in a test environment. Both test benches had to allow for improved accessability to the steering system and should enable an efficient analysis and assessment of possible solutions after the tests had been conducted. In order to realise adequate test benches, the relevant incitement parameters (external load, steering wheel angle, etc.) were determined during road tests.

Figure 4 shows the design of the rattling test bench. Different to the actual vehicle, the steering system's pump is powered by an electric motor. All other components, such as pressure lines, coolers, oil tanks, etc. are arranged corresponding to the test vehicle. The steering system is moved against a spring-mass system from a center position to the left, and thus pressure is induced on the system, which is equal to the pressure that had been measured in the respective cylinder chamber during a road tests, shortly before driving over the obstacle. The steering wheel is fixed in this position. A Hydropulser, consisting of a servo cylinder and a fast control valve, is inducing the same sudden load onto the system, which is equal to the data collected in the road test with the help of strain gauges attached to the steering links.

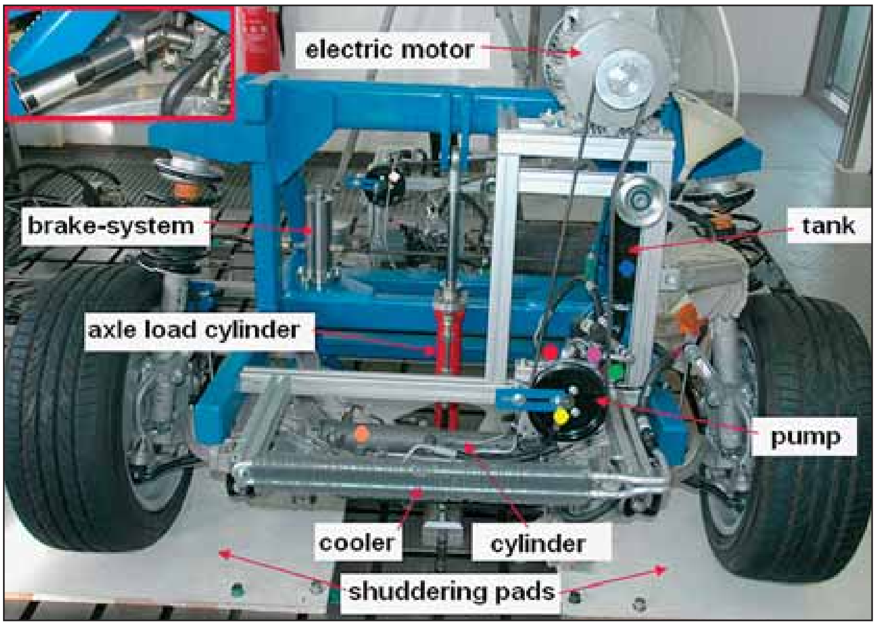

Figure 5. *Test bench for shuddering*

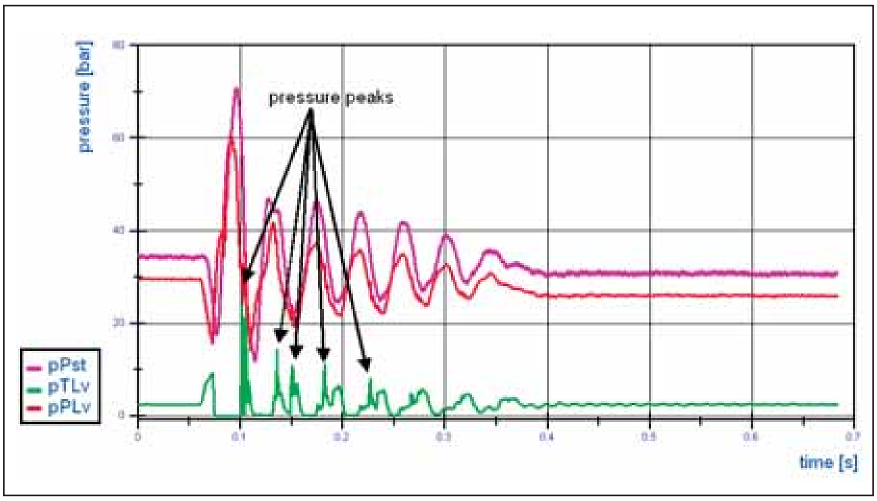

Figure 6. *Pressure signals during rattling*

Various sensors are installed on the test bench, which determine the relevant system parameters. The determination of pressures is established by sensors attached to the pump outlet (**pPst**), at the steering valve inlet (**pPLv**) and steering valve outlet (**pTLv**). Next to these, the load on the cylinder by the hydropulser (**Fkb**), the rack displacement (**ykb**) and the tank temperature (**tT**) were plotted. In addition, the angle at pinion gear (**delta_phi**) and the rotation speed of the pump (**nP**) were also monitored.

Because shuddering is determined by the contact between tire and surface, it is imperative that the test bench also includes a front axle corresponding to that of the test vehicle. The shuddering test bench is shown in *figure 5*. In analogy to the rattling test bench, the pump is also fed by an electric motor. Further components (lines, steering gears, cooler, oil tank, wheel suspension, etc.) corresponded to the design of the test vehicle. A manually adjustable piston served as braking system, in order to carry out steering manoeuvres with enganged front wheel brakes. To simulate the weight of the engine, a clamped-on cylinder is used in simulating the axle load of the test vehicle. The characteristic steering profile is simulated by a position-controlled electric motor, which is shown in the top left corner of figure 5. The profile, which is steered by the electric motor, had been determined beforehand in a road test and assigned on the test bench. A major task of the test bench consists in simulating the stick-slip effect, which occurs during road test, thus shuddering pads are installed between tires and machine base. To determine the various system parameters, the sensors which are applied in the rattling test bench are installed in similar manner. Thus, pressure, rotation speed, displacement and temperature can be measured.

With the help of the pressure readouts from both test benches, an analysis and identification of the accoustic phenomena can be accomplished.

The readouts from the pressure sensors at the rattling test bench are given in *figure 6*. The pressure curves clearly show an incitement of the steering system through the hydropulser at 0.07 seconds.

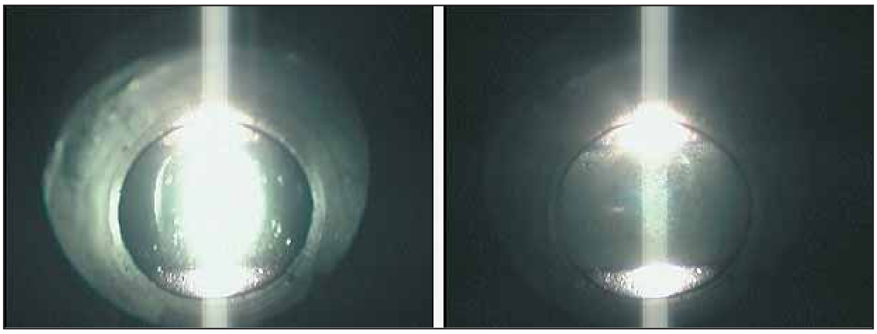

Figure 7. *Cavitation bubbles in the return line*

This incitement simulates the conditions experienced while driving the vehicle over an obstacle. In the return line of the power steering system, at first an increase of pressure up to ca. 12 bar is evident (**pTLv**), then a sharp drop to 0 bar; which is then followed by sharp pressure peaks. It is this drop to a 0 bar pressure level and the subsequent sharp pressure peaks - caused by a vibrating gear rack that sets the steering valve oscillating - that explains the characteristic rattling noise.

The rattling experienced on the test bench constitutes a dampened vibration which fades away after a couple of cycle periods, exactly as found under road test conditions. Thus, next to the measured pressure pulsations, the oscillating steering valve has also to be responsible for the unsteady volumetric flow in the return line. The pressure drop to 0 bar, and the subsequent pressure peaks could even lead one to presume that cavitation is taking place. This initial assumption was confirmed in a test in which a visible section was integrated into the return line [1]. *Figure 7* shows the flow channel in the visible section.

The left image shows the normal condition. The flow channel contains a transparent flow, which is illuminated by a source of light beneath the visible section. When the rattling phenomenon commences, the flow channel is temporarily darkened by cavitation bubbles and the light source will only illuminate the upper and lower margin of the vision panel.

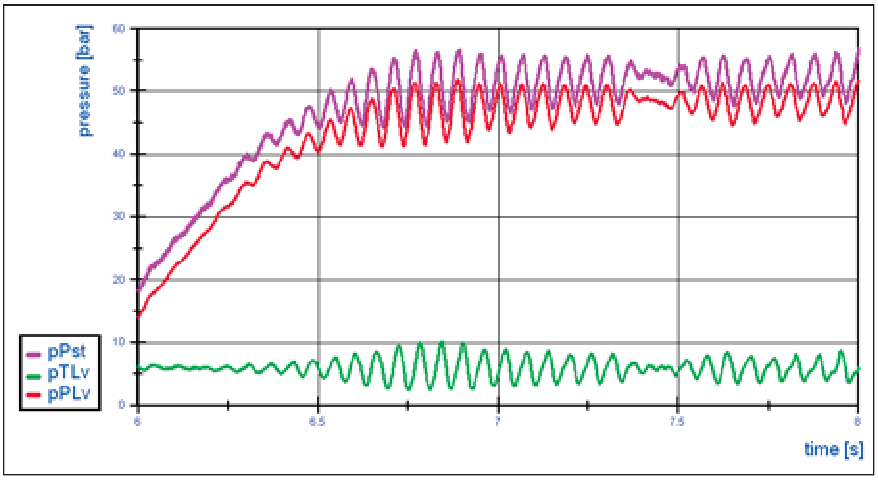

Figure 8. *Pressure signals during shuddering*

The pressure curves during shuddering are shown in *figure 8*.

If the steering wheel is moved from its central position, the pressure in the steering system increases up to 40 bar. Next, the linear increase of system pressure is superimposed by a periodic pressure oscillation, which can be measured at the high pressure side of the steering valve (**pPst**, **pPLv**), as well as on the low pressure side (**pTLv**). The pressure pulsations during shuddering are significantly lower in frequency at 20 Hz than during rattling. Steering movements on critical surfaces lead to stick-slip effects on the tires that set the entire steering system pulsating, which is facilitated by an inappropriate front axle geometry and wide tires. Next to the disturbing noise, this periodic pressure oscillation leads to a fluctuation in steering wheel torque, which is experienced as a shuddering sensation by the driver.

Troubleshooting

To eliminate both noise phenomena - rattling and shuddering - an additional component was to be developed, which can be integrated into the existing steering system. According to the results obtained from the test benches, a reduction of pressure fluctuation in the steering system would correspond to a reduction in noise in the entire system, for rattling as well as for shuddering.

The integration of an additional component into the pressure line was not an option though, because resonators were already installed in the pressure line as a standard measure to reduce pump pulsation.

Possible solutions to reduce pulsation of power steering systems have already been thoroughly treated by [2, 3]. A solution for the return line has to meet the following requirements, set by BMW:

- The additional component is integrateable into the return line of the steering system
- Minimal drop in pressure under normal conditions
- The point of activation must be detected without electronic sensors
- To minimize pressure oscillation no external source of energy is used
- Simple design of the additional component

Prior to developing a new solution, existing production-model solutions were examined and their pros and cons analyzed. There are two orifices integrated into the production-model

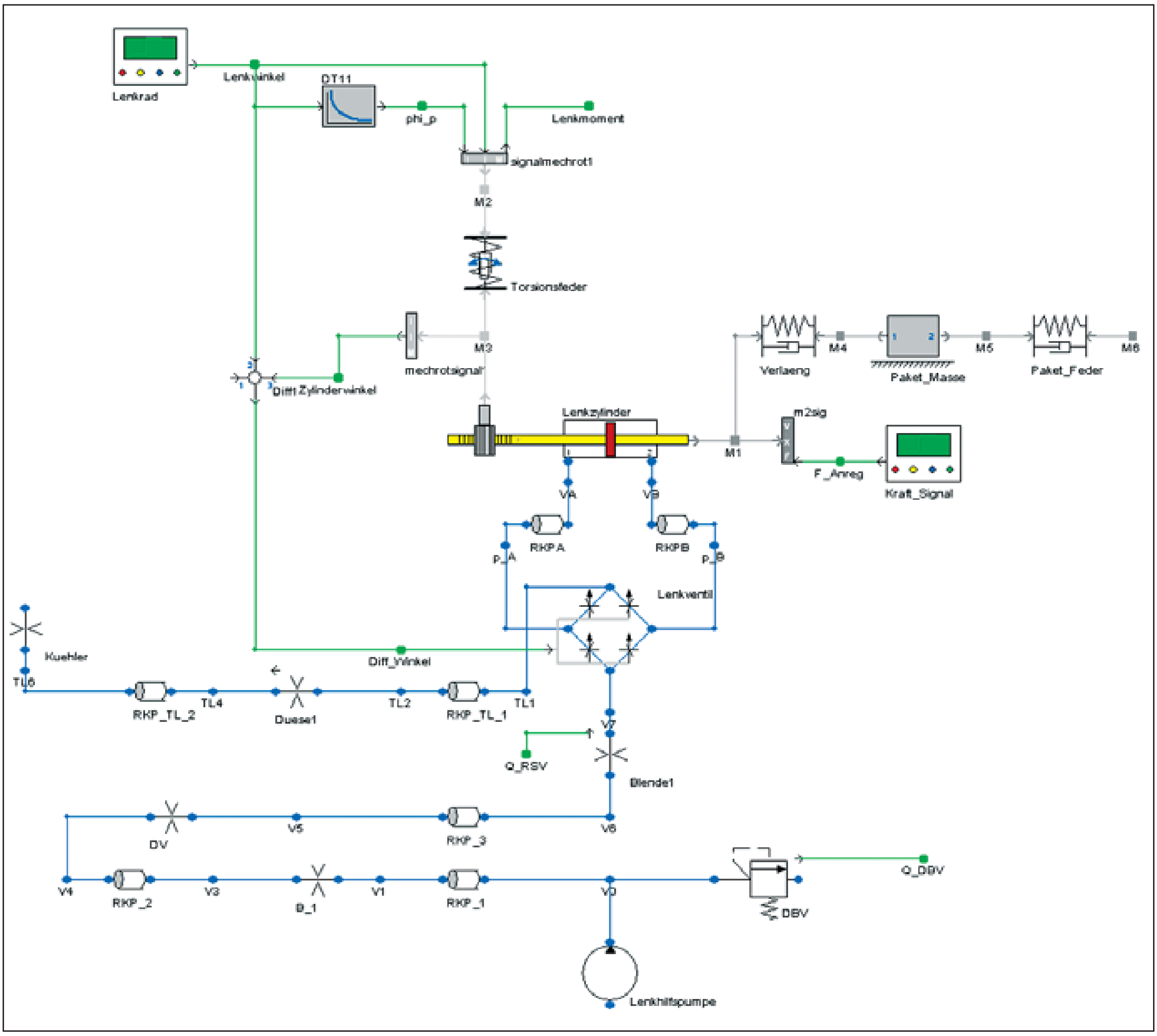

Figure 9. *Simulation model of the steering system*

return line, which produce constant pressure drops. Because of these orifices, a back pressure is building up downstream from the steering valve, which counteracts the 0 bar pressure level in the case of rattling and thus antagonises the formation of cavitation. However, the increased pressure drop also creates an increase in the steering system's energy consumption.

This additional resistance also leads to a shift in the eigenfrequency of the entire system, thus shuddering is – compared to a return line without orifices – reduced but not eliminated. Thus, next to a higher pressure drop in the return line, the orifices are also responsible for a modified line capacity. The hydraulic capacity can be calculated, as shown in Eq. (1):

$$C(p) = \frac{dV}{dp} \quad (1)$$

An increased pressure drop at a constant tube-chamber volume leads to a lower capacity and thus to a higher stiffness of the return line. In order to determine the consequences of a change in capacity on rattling and shuddering, a simulation model (as shown in *figure 9*) was built up in DSH*plus*.

In the simulation, the capacity of the individual tubes can be parameterised in the contact points of the hydraulic components, termed volume knots. The simulation results show, that no rattling will occur in a soft return line with a high capacity. In the case of shuddering however, it is imperative that the return line is hard and of little capacity, in order to prevent self-induced pressure oscillations.

This means, that the return line has to be designed with little capacity, which must be increased significantly by a control element if rattling should occur. In order for the control element to be able to distinguish between rattling and shuddering, the decrease in pressure at the measuring orifice is used as a triggering signal.

Since rattling will cause an impulsive increase of volumetric flow through the system in contrast to shuddering, the drop of pressure at the measuring orifice will be significantly higher, which also results in an increase of the load acting on the orifice. This increase of load can be used to activate the control element. A decisive advantage over the production- model solution is constituted by the fact, that the diameter of the measuring orifice can be dimensioned a good deal larger than the diameter of the original orifice plate. This is due to the fact that it does not have to function in building up back pressure. The design of a first prototype is shown in *figure 10*.

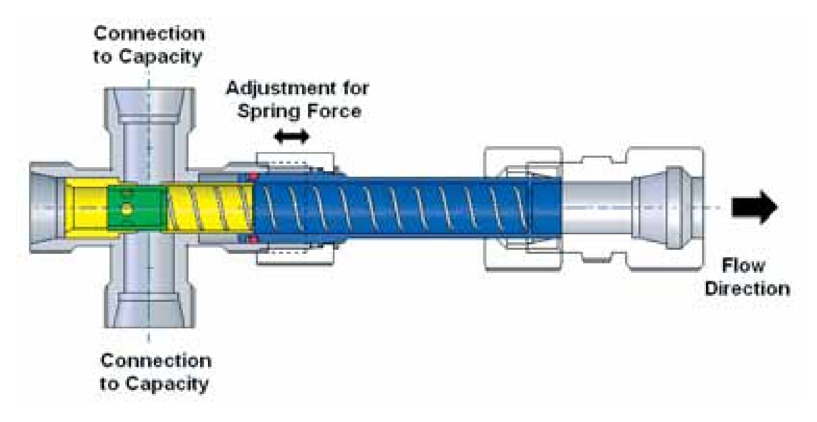

Figure 10. *Sectional view of first prototype*

The prototype is based on a cross-connection through which the fluid flows from the left side to the right. The top and bottom plugs of the cross-connection are connected with a capacity. The control element is designed as a slider, which generates a pressure drop, dependent on the volumetric flow. If the volumetric flow rises up to a switch point, the slider moves to the right against the spring force and opens a connection to the capacity through its radial holes. The elasticity can be adjusted with a lock nut.

The capacities used are flat tubes made by ContiTech, which excel in their volumetric expansion ability. Design results for the rattling test bench with an installed prototype are shown in *figure 11*.

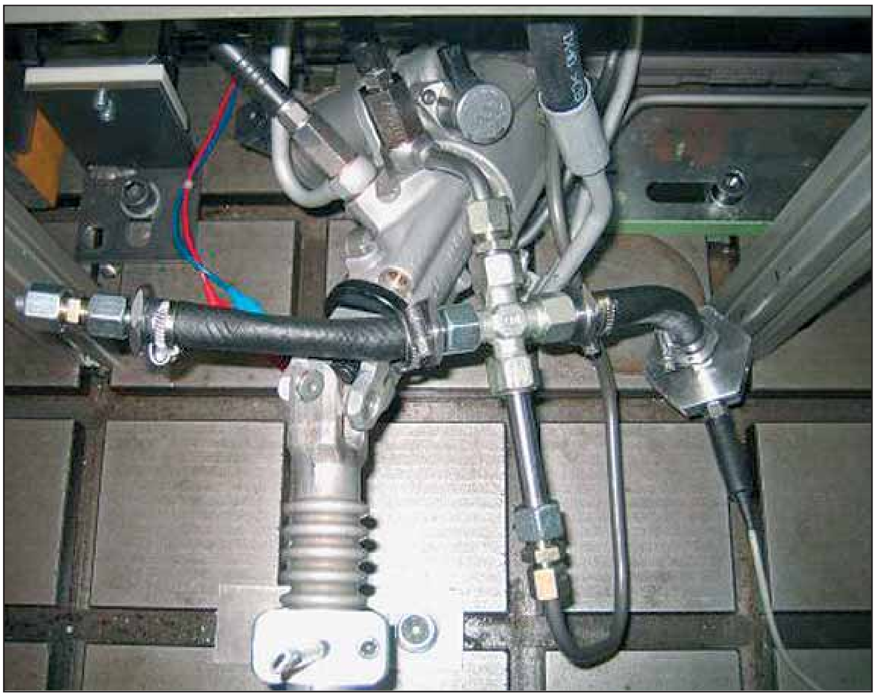

Figure 11. *Prototype on the rattling test bench*

Both flat tubes were attached as dead ends to the cross-connection. When rattling, there was clear evidence of breathing visible at the flat tubes, which was not the case during shuddering. This fact already indicates the functionality of the prototype valve. The plotted pressure signals verify it.

Conclusion

During rattling (see *figure 12*), there is no evident pressure drop and no pressure peaks caused by cavitation. The additional capacities integrated into the system by means of flat tubes, smooth the pressure curve in the return line.

Although the incitement of the steering system by the impact of the hydropulser is clearly visible at 0.075 sec, there is no periodic oscillating pressure, as had been the case before (compare to figure 6). Acoustically, the impact of the hydropulser is now only audible as a dampened noise, which subsides immediately.

The prototype also has a positive effect on system behavior during shuddering (see *figure 13*). In this loading case, both capacities are shut off from the rest of the system by the closed valve slider. The return line has a lower capacity and thus a higher stiffness.

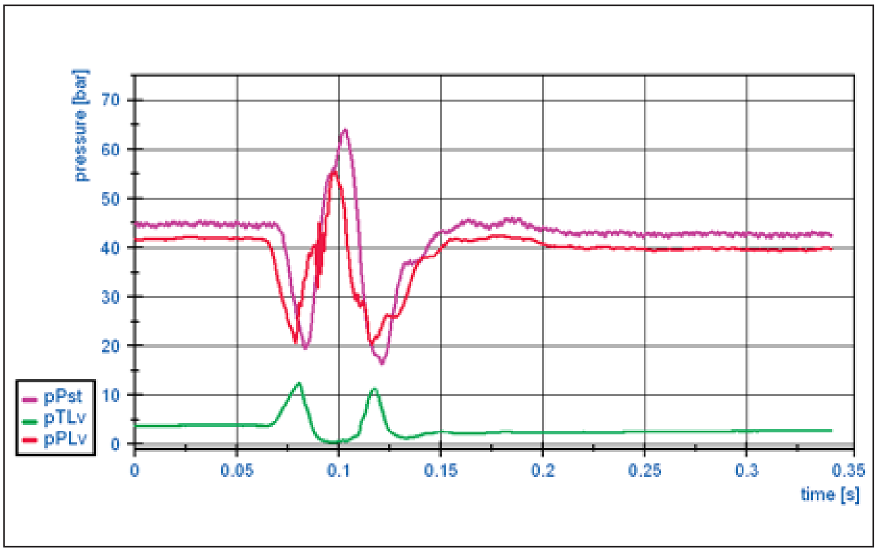

Figure 12. *Pressure signals during rattling with integrated prototype*

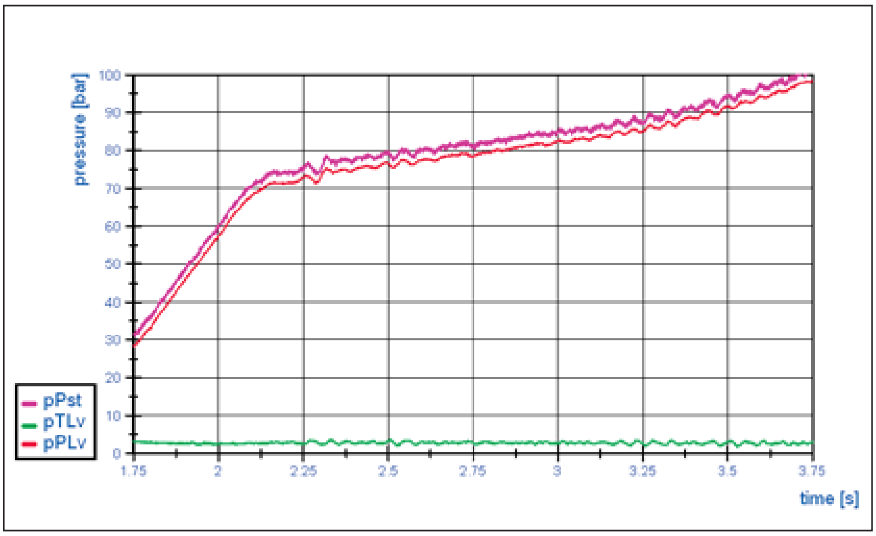

Figure 13. *Pressure signals during shuddering with integrated prototype*

Compared to the results of measuring shuddering in the standard production-model line (see *figure 8*), pressure pulsations in the return line could be significantly reduced. At the same time, the pressure amplitude was lowered on the high pressure side, downstream from the steering valve. Thus, a positive effect on steering wheel torque can be sensed by the driver, since no shuddering can be felt on the steering wheel while at a standstill on smooth surfaces.

By means of integrating the valve prototype into the return line of the steering system, a significant reduction of pulsating pressure during rattling as well as shuddering can be achieved. The reduction of pulsation leads to an elimination of the disturbing noise, which is clearly audible when the product-model line is used in the return line. In addition, the integration of the valve prototype leads to the removal of the two orifices of the product model line, thus leading to a reduction of the overall system pressure drop. This leads to increased fuel efficiency for the entire steering system. The radial arrangement of the flat tube around the steel tube would furthermore constitute an improvement in design, saving installation space.

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Snovanje in preizkušanje inteligentnega energetsko učinkovitega ventila za zmanjšanje pulziranja tlaka v avtomobilskih volanskih krmilnih sistemih

Razširjeni povzetek

V prispevku je prikazana raziskava problema glasnosti oz. hrupa in tresljajev, ki jih povzroča volanski krmilni sistem avtomobila. V skupnem raziskovalnem projektu Inštituta IFAS in podjetja BMW sta bila podrobneje analizirana dva dobro znana hidravlična pojava, kot sta tresenje in glasnost volanskega krmilnega sistema pri premagovanju ovire na cestišču ob majhni hitrosti avtomobila in pri vrtenju volanskega obroča oz. premikanju koles avtomobila na mestu. Oba problema se pojavita predvsem pri upravljanju avtomobila na parkirišču oz. pri obračanju. Glavni cilj raziskave je bil zmanjšanje hrupa, ki ga povzroča volanski hidravlični krmilni sistem. Prispevek podaja predvsem del analize in sklepne ugotovitve raziskave, kjer je za rešitev obeh negativnih hidravličnih pojavov predlagana integracija inteligentnega in energetsko učinkovitega ventila v povratni hidravlični vod volanskega krmilnega sistema. Vključeni ventil vpliva na spremembo togosti povratnega hidravličnega voda v odvisnosti od obeh hidravličnih pojavov in ne vpliva na občutljivost volanskega sistema. Raziskovalni projekt je bil razdeljen v tri sklope.

Prvi sklop raziskave je vključeval analizo volanskega krmilnega sistema za osebni avtomobil BMW serija 5. V okviru te analize sta bila izmerjena in podrobneje analizirana dva pojava, in sicer nenadno pulziranje tlaka olja, katerega posledica je hrupnost volanskega krmilnega sistema, kakor tudi periodično nihanje tlaka, ki povzroča tresljaje sistema in posledično tudi hrup. Posledica obeh pojavov je moteč hrup v potniški kabini avtomobila, ki se pojavlja predvsem v določenih elementih vožnje, kot je npr. vožnja čez ovire ali parkiranje.

Drugi del projekta je vključeval gradnjo dveh preizkuševališč, ki sta omogočila laboratorijsko reprodukcijo obeh zgoraj opisanih pojavov, in sicer neodvisno od avtomobila. S primerjavo realnih podatkov, pridobljenih z meritvami med vožnjo avtomobila, s podatki, pridobljenimi na preizkuševališčih, je bila dosežena verifikacija preizkuševališč, predvsem njihova funkcionalnost in natančnost. Druga prednost preizkusne naprave je ta, da omogoča enostaven dostop do komponent volanskega krmilnega sistema. Spremembe za izboljšavo sistema oz. modifikacije so zato lahko izvedene v krajšem času in z manjšimi posegi kot na avtomobilu.

V tretjem delu raziskave je bil razvit nov, inteligenten, energetsko učinkovit ventil za uporabo v volanskem krmilnem sistemu in analiziran v okviru preizkusov na obeh preizkuševališčih. Nov ventil lahko zazna oba problematična zgoraj opisana hidravlična pojava brez uporabe senzorskih signalov in brez povzročanja visokih padcev tlaka. V primeru nastopa nenadnih hidravličnih udarov in ropota sistema naredi ventil povratni hidravlični vod volanskega krmilnega sistema manj tog, v primeru periodičnih nihanj oz. tresljajev pa ventil ta vod otrdi oz. povzroči povečanje njegove togosti. Mehkejši povratni vod zmanjša vpliv pulziranja tlaka, medtem ko je bolj tog povratni vod manj občutljiv za periodična nihanja tlaka.

Ključne besede: volanski krmilni sistem avtomobila, hrup, tresljaji, pulziranje tlaka, tlačni udar,

Nomenclature

delta_phi : angle at pinion gear
C : hydraulic Capacity
F : external load on steering cylinder
Fkb : load an cylinder by hydropulser
nP : rotation speed of pump
Δp : pressure change
pPst : pressure at pump outlet
pPLv : pressure at steering valve inlet
pTLv : pressure at steering valve outlet
tT : tank temperature
ΔV : volume change
ykb : rack displacement

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