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Foreword

Innovations are shaping our future. Experts predict that there will be more changes in the fields of transmission, electronics and safety of vehicles over the next 15 years than there have been throughout the past 50 years. This drive for innovation is continually providing manufacturers and suppliers with new challenges and is set to significantly alter our world of mobility.

LuK is embracing these challenges. With a wealth of vision and engineering performance, our engineers are once again proving their innovative power.

This volume comprises papers from the 7th LuK Symposium and illustrates our view of technical developments.

We look forward to some interesting discussions with you.

Bühl, in April 2002

Helmut Beier

President
of the LuK Group

Content

Demand Based Controllable Pumps

Reduced Power Consumption in Power Steering, Active Chassis and Transmission Systems

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Dirk Webert
Thomas Scholz
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Introduction

Hydraulic systems are used in passenger cars to improve their safety and comfort. The well-known benefits include high power density, a low power-to-weight ratio and excellent dynamics. Hydraulic systems are often cited, however, as consuming more power in comparison to controlled electric drives, thus increasing fuel consumption. But by selecting the right type of pump in conjunction with demand based control, the power consumption associated with pumps can be significantly reduced. One widely used method is the speed-controlled electric motor for pumps up to approximately 0.5 kW power. In this paper, we will only consider higher power applications. In these applications the combustion engine is used as the prime mover.

Here are three examples:

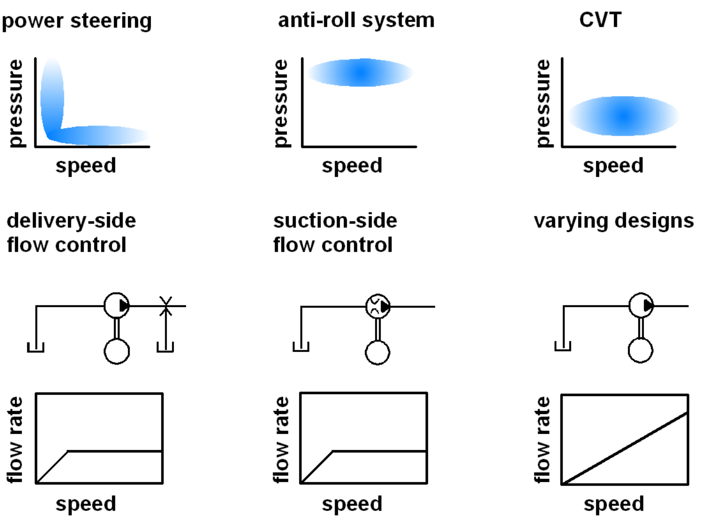


Fig. 1: *Examples of Pump Applications*

In **power steering** (open center), the pump often runs at very low pressures. Delivery-side flow rate control has been the state-of-the-art for decades.

Anti-roll systems with accumulators have high continuous pressures over the entire speed range. Suction-controlled radial piston pumps have proven useful in this regard.

In **continuously variable transmissions (CVT)**, the maximum pressures and speeds are lower, but moderate pressures are often achieved. Different types of pumps can be used.

Pumps for Power Steering

Open Center Steering Systems

In automotive vehicles, the power steering is usually designed as an open center system (see figure 2).

These are characterised by the fact that the flow is pumped through the system at a low pressure when driving straight ahead.

For quick steering actions, a flow controller constantly provides the maximum flow. However, for standard steering manoeuvres, a markedly lower flow is needed.

High pressures occur only when steering at a standstill or at low driving speeds.

The pumps for such open center steering systems are generally designed as fixed displacement vane pumps and powered by an engine-driven belt. The pump flow rate thus rises linearly with the engine speed. Since the steering requires only a limited flow rate, a flow controller diverts the excess flow in the pump so that it is circulated internally. The pump cannot be controlled based on any other driving parameters, such as vehicle speed.

Such systems cause approximately 2% greater vehicle fuel consumption in fuel economy tests (NECE).

It is one of the development goals for current steering systems to reduce this additional fuel consumption and to tailor the function more closely to the driving condition. At the same time, the steering comfort and dynamics of today's systems must be maintained or even improved. The limited space in the vehicle must be taken into consideration here as well.

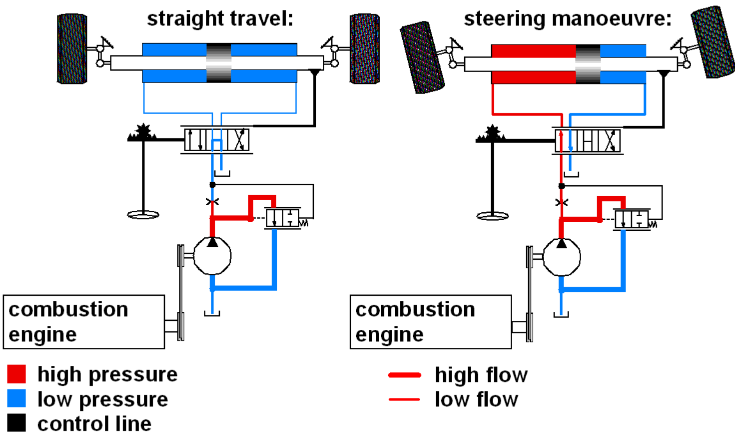


Fig. 2: *Open Center Steering System*

Electrically Variable Volume flow (EV^2)

The rate of flow can be adjusted electrically by installing an electrically controlled bypass valve in addition to the existing flow controller (see figure 3). Here, the flow control is implemented using a full flow control piston, as has proven successful in the basic pump. A bypass is created parallel to the full flow throttle. A proportional valve is incorporated in this bypass, which controls a variable bypass flow.

Since the full flow control piston is designed according to the principle of a 'pressure balance', the pressure drop across the full flow throttle and the bypass valve are kept constant. This means the flow that passes through the bypass is proportional to the size of the valve opening. The system pressure, which again depends on the driving condition, has no effect. Therefore no additional pressure sensing function is needed.

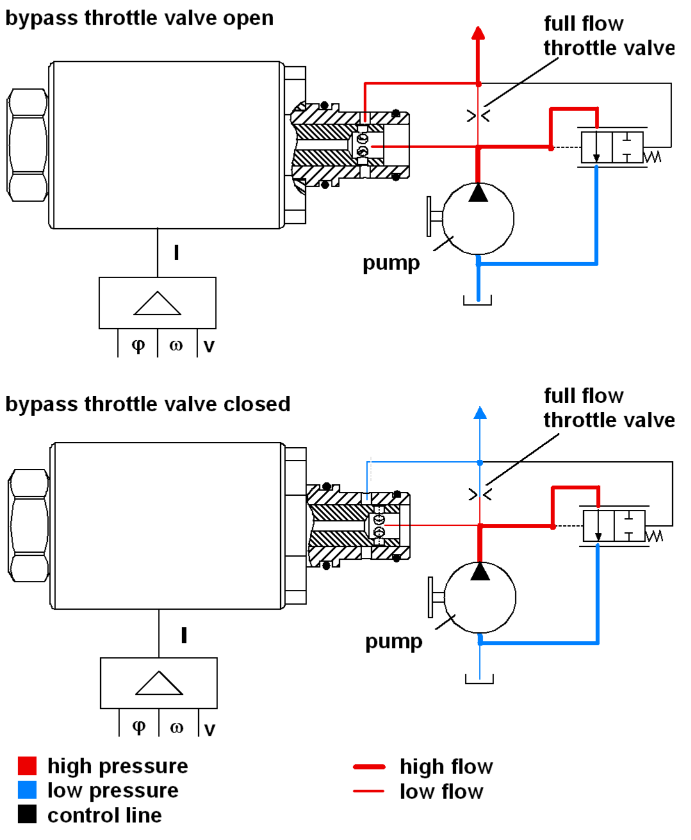


Fig. 3: *LuK-EV² (Electrically Variable Volume flow)*

The opening travel of the bypass valve can be varied via electronic control as a function of driving condition parameters, such as driving speed (v), steering angle (φ) and steering angle speed (ω). The flow rate is adjusted to suit the driving condition. Thus the flow condition rate reduces in situations where no steering assistance is required. Since the pressure drop changes quadratically with the flow rate, a relatively small drop in flow causes a marked reduction in the pressure drop and thus a reduction in the hydraulic power consumption. As shown in the trace in figure 4, adjusting the flow based on demand reduces pressure in one extreme example from 10 bar to 1 bar.

The deciding factor for the energy savings while maintaining steering comfort is the pump dynamics. If an input parameter is changed quickly, for example the steering angle speed during an evasive manoeuvre, the pump must be able to adjust the flow rate to the new conditions fast enough so that the driver does not notice the adjustment. The LuK solution is able to increase the flow rate from the minimum to the maximum within 30 ms. The driver can detect no difference in the steering wheel compared to the standard system.

Demand based flow rate adjustment in the new European driving cycle (NECE) achieved consumption levels of approximately 1% less than conventional steering systems.

By making the flow control dependent on the driving parameters, it is possible to realise additional comfort features with the pump. In this way, it is possible to program the system so that the flow rate is dependent on the driving speed. With conventional systems, the delivery rate of the pump is dependent solely on the engine speed. Reducing the flow with increasing vehicle speed increases the steering torque, which the driver perceives as stiffer, more direct steering. Furthermore, the flow can be significantly restricted just before reaching the steering end stop. This damps the steering end stop.

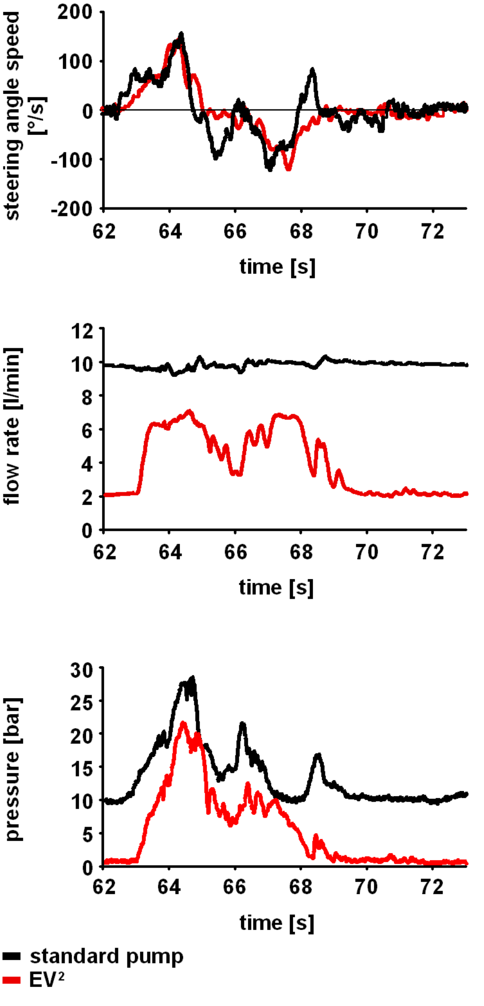


Fig. 4: Comparative Measurement of Standard Pump versus EV² when steering through a Curve

Installation in the Vehicle

The solution presented here is characterised by the fact that the arrangement of the valve with regard to the pump pressure port can be very flexible. Since the bypass valve diverts only part of the flow, and the pressure difference is small, the valve can be designed very compactly. The required magnetic force, and thus the current draw, of the valve remains low. Since the valve adjustment has a direct effect on the flow rate, the system is very easy to control.

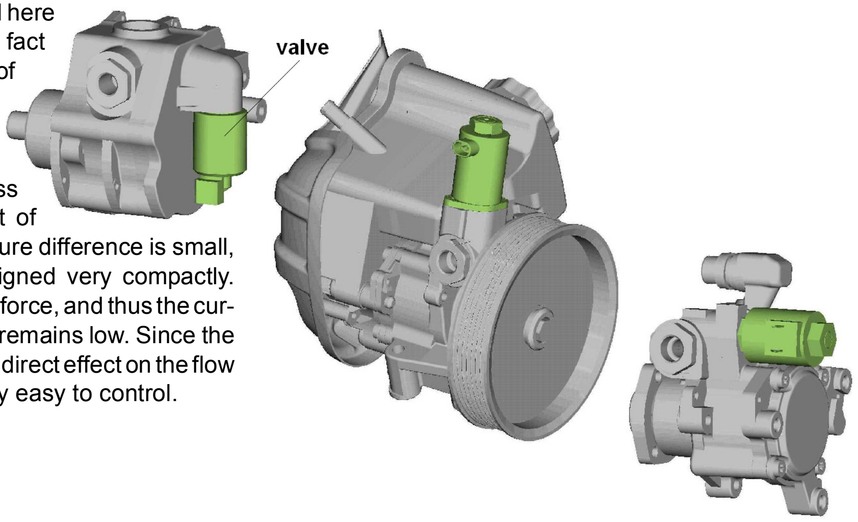


Fig. 5: *EV^2 Mounting Variations*

Advantages of EV^2

- Approx. 50% lower power consumption of the pump (approx. 1% less fuel consumption)
- Reduced cooling complexity in the system
- Improved steering comfort
- Steering force matched to the driving condition

Hydraulic Chassis Pumps for Active Chassis Systems

Active chassis have been a goal of automobile designers for a long time. Active in this context means active compensation of body movements. All of the systems designed use hydraulic components. Recently two different concepts using LuK pumps have been technically implemented.

Open Center System

Examples:

Active **C**ornering **E**nhancement (Land Rover off-road vehicles)

Dynamic **D**rive (BMW luxury/sport class)

Both systems provide roll compensation. The radial piston pump (RPP) with internal suction control provides a constant flow rate.

Closed Center System

Example:

Active **B**ody **C**ontrol (DaimlerChrysler luxury/top class)

The ABC system features compensation for pitching motions of the body in addition to roll compensation. Level regulation is also integrated. An internal and external suction-controlled radial piston pump is used to supply the pressure. This type of pump is able to deliver the required flow rates of 1 - 12 l/min at 200 bar system pressure.

Fixed-displacement pumps are of only limited use because of the maximum power requirement of up to approx. 20 kW.

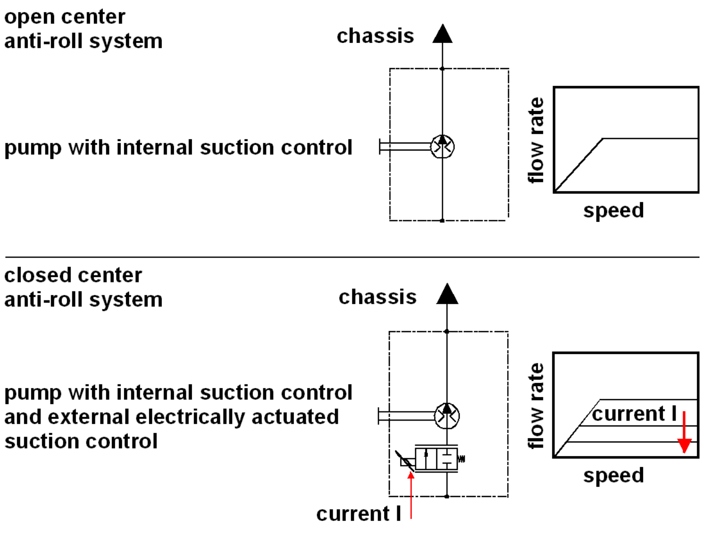


Fig. 6: Pump Control for Anti-Roll Systems

Function of the Suction-Controlled Radial Piston Pump

The filling of the pistons, which are internally actuated and subject to external pressure, is controlled by grooves on the low pressure side and by valves on the high pressure side.

The general function of the suction-controlled radial piston pump is shown schematically in figure 7.

As the piston drops from the top dead center point, a vacuum is created in the piston chamber (hollow vacuum regions are shown in yellow in figure 7). This continues until the suction holes on the side of the piston connect with the suction side so that oil flows into the piston. The filling stops after further rotation of the eccentric shaft beyond the bottom dead center point, when the suction holes again close. This results in a no-flow angle, which is determined purely by the geometry.

The diagram shows three different conditions in which a suction-controlled RPP can operate.

In the top diagram in figure 7, the RPP is in non-regulated mode, in which the pump acts as a fixed-displacement pump. The piston chamber is completely filled with oil and the flow rate increases as the pump speed rises.

The middle diagram in figure 7 shows that as the piston speed (pump speed) increases, the fill time is no longer sufficient to fill the piston chamber completely. This causes a larger no-flow angle.

This behaviour of the suction-controlled radial piston pump is called internal suction throttling. This internal suction throttling is very significant from an energy standpoint. If the piston chamber were always filled completely with oil, both with increasing engine and pump speed, a fixed-displacement pump would exist across the entire speed range. The suction throttling prevents this. Above a certain speed, less and less oil enters the piston chamber. The flow rate remains nearly constant with increasing speed. Only the desired amount of oil per unit of time is pressurised with addition of energy. Suction throttling thus provides variable flow and allows the power requirement to be lowered up to 75% compared to a fixed displacement pump, with little design effort.

The externally controllable suction throttling shown **in the bottom diagram in figure 7** is achieved by including a valve in the suction line. This lowers the pressure in the suction chamber and decreases the pressure difference that arises when filling the pistons. Even less oil can now flow into the cylinder, further lowering the power consumption and the flow rate of the pump. The power requirement drops by up to 90% compared to a fixed displacement pump.

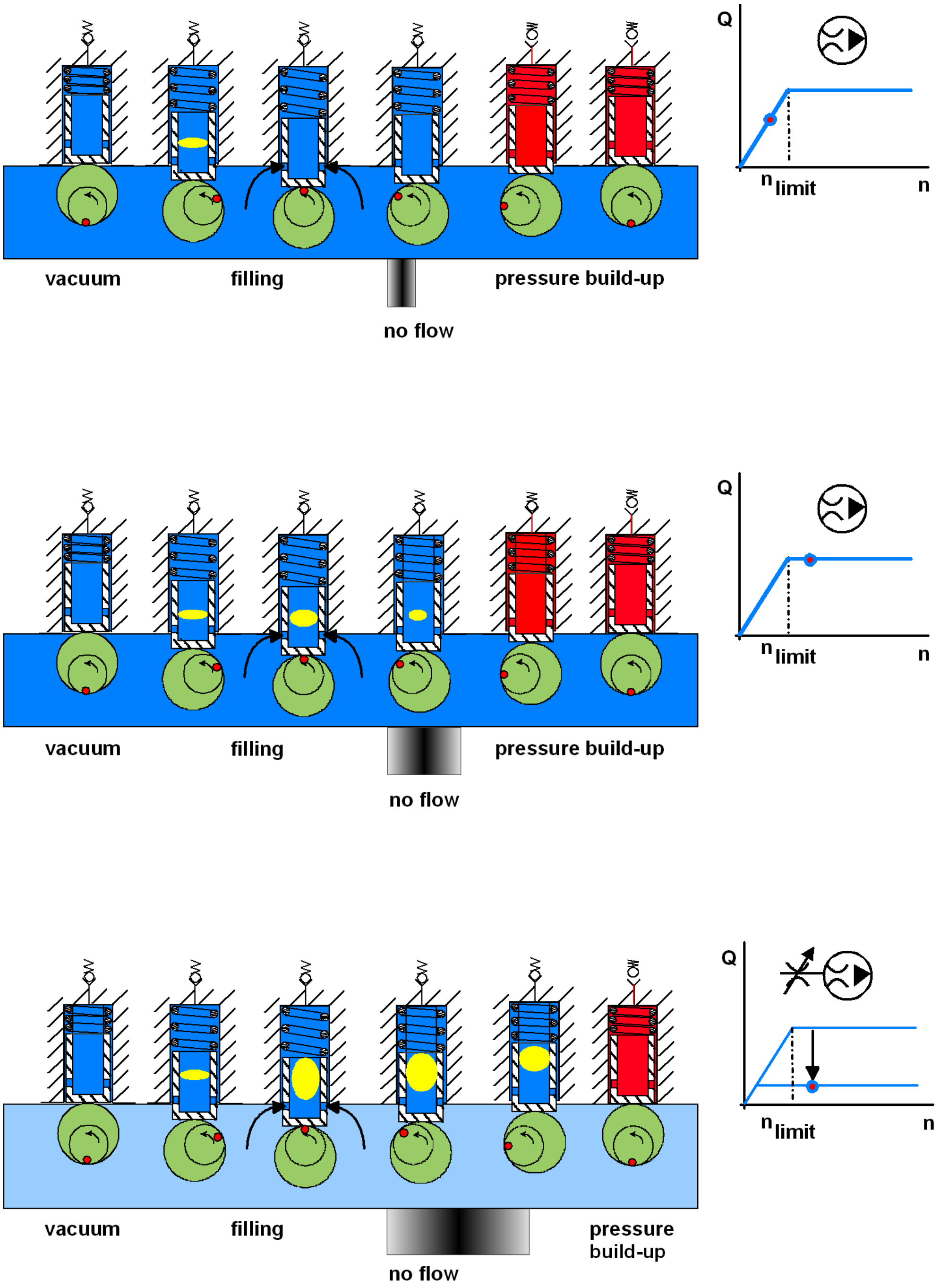


Fig. 7: Operating Principle of a Radial Piston Pump

Noise Optimisation

The pumping principle of the suction-controlled radial piston pump is known for its low power consumption. Its main disadvantage is its comparatively high flow pulsation or airborne-noise radiation. Power consumption drops as the no-flow angle increases, whereas the pressure pulsation increases.

In order to meet the requirement for very low noise levels in top of the range vehicles, development must focus on noise reduction. Figure 8 shows an example of a successful development.

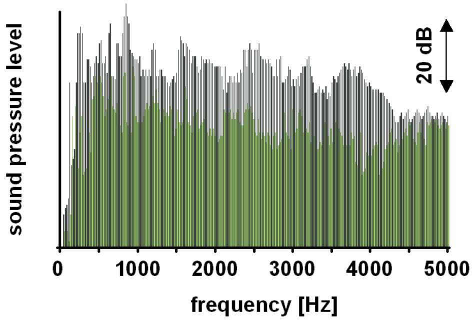


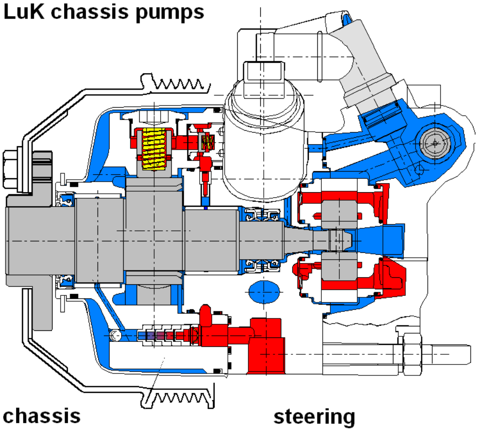
Fig. 8: Airborne-Noise Radiation of a Radial Piston Pump

The airborne-noise radiation is shown over the frequency for two different development stages. The following measures were successful in lowering airborne noise by about 20 dB:

- Detailed design of the outlet check valves in plate form
- The use of vibration-damping plastics for the belt pulley instead of sheet steel
- Partial increases in stiffness of the housing parts

Installation in the Vehicle

LuK chassis pumps



chassis	**steering**
V_{geo} = 6 - 6,7 cm³	V_{geo} = 8,4 - 15 cm³
p_{max} = 200 bar	p_{max} = 135 bar

Fig. 9: *Radial Piston/Vane Tandem Pump*

Due to the very limited space in the engine compartments of high-performance vehicles, a tandem arrangement with the power steering pump helps make it possible to install this additional pump. In this way, no additional room is needed in the belt drive or on the engine. In addition, the tandem construction also reduces the weight. A second pulley and the second pump bracket can be eliminated.

Advantages of Suction-Controlled RPPs

Active chassis systems were first technically possible in production with the development and noise optimisation of relatively large suction-controlled radial piston pumps.

- Power consumption with external suction-control is up to 90% less than with fixed displacement pumps
- Electric actuation allows integration with system controls
- Radial construction makes it well suited for tandem pumps
- Acceptable noise level

High-Pressure Transmission Pumps

In today's automatic transmissions for passenger car applications vehicle take-up, gear ratio selection, actuation of the reversal clutch set for forward/reverse driving, cooling and lubrication are all controlled by hydraulics. This requires a hydraulic power unit and a hydraulic control system.

The trend towards greater comfort and, at the same time, increased performance has led to the development of continuously variable transmissions. The hydraulic controls of continuously variable transmissions operate at significantly higher maximum pressure levels (>30 bar) than conventional step transmissions (<20 bar). This presents a technological challenge for the transmission pump development, since in contrast to other hydraulic applications in the vehicle, transmission pumps sometimes operate with highly aerated automatic transmission fluid. This results in special technical challenges regarding noise and wear.

We now have the task of selecting a power unit that meets a wide range of hydraulic requirements and satisfies the demands of the automotive industry.

Development Goals

Hydraulic Requirements

- Pressure range up to max. 85 bar
- Speed range 600 ... 8000 min^{-1}
- Temperature range –40 °C ... +150 °C
- Low to high proportion of entrapped air in the transmission oil

Power Consumption

- Good volumetric efficiency at higher pressures, since this determines the pump size
- Good hydraulic-mechanical efficiency at low to medium pressures and speeds up to 2500 min^{-1}, since this is a major factor in fuel consumption
- Low power consumption at high speeds and medium pressures; a decisive factor for maximum vehicle speed, maximum acceleration and the transmission's cooling oil requirements

Noise

- Acceptable pump noise levels in all areas of hydraulic requirements

Cold-Start Capability

- The transmission pump's self-priming function must be guaranteed under all conditions

Design Comparison

Figure 10 shows an initial comparison of different potential pump principles, from the point of view of the torque consumption, as a function of pump speed.

All of the pumps shown are scaled so that at a speed of 1000 min^{-1} and pressure of 20 bar, the flow rate is 10.5 l/min. This means that pumps with better volumetric efficiency have a smaller nominal displacement. At the same time, a flow rate of 15 l/min is assumed to be sufficient to supply oil for all functions of the transmission control. The variable displacement pumps (variable displacement vane pump and suction-controlled radial piston pump) are regulated to provide a constant flow rate of 15 l/min. The dual-flow vane pump with a 50:50 split still delivers a minimum of 15 l/min at 3000 min^{-1} (red arrow) after offloading one half of the pump.

For vehicles with high-performance engines, the use of fixed displacement pumps is beneficial, since most driving is done at low engine speeds. The effect of the higher power consumption on the maximum speed is slight due to the progressive tractive resistance characteristic.

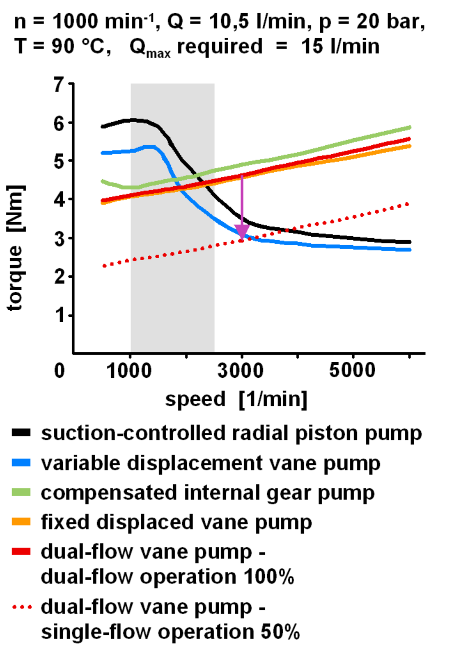


Fig. 10: *A Comparison of the Torque Consumption of Different Pump Designs*

For vehicles in the medium performance range, the use of variable displacement pumps does not serve our objectives, since they are more expensive and require a great deal of space. A good solution is to use the dual-flow vane pump in this segment.

Compensated Internal Gear Pump

The internal gear pump is currently the most frequently used type of pump for step transmissions. The volumetric efficiency can be matched to high-pressure use by gap compensation.

The axial gap compensation is based on pressing the axial pressure plates against the gears on both sides, whereby the outer areas of applied pressure are greater than those on the toothed wheel side. A slight force presses the plates against the rotating ring and pinion gears, thus minimising the gap.

For radial gap compensation, hydraulic fluid enters a split crescent seal, which expands and comes to rest on the rotating gears.

The benefits of this type of "full-contact" gap compensation come to bear particularly with pumps that are placed on the torque converter pump hub, since the pump is designed very large here due to the geometry, and wide leak paths occur.

The inner gear crescent pump with sickle is further characterised by low kinematic flow pulsation. The specific control of the pressure transitions over a large angle of rotation has a positive effect on the pump noise with aerated transmission oil.

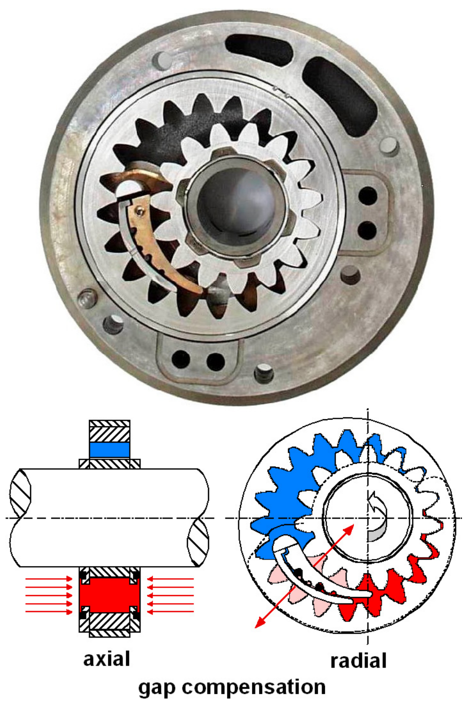


Fig. 11: *Gap Compensation in an Internal Gear Pump*

Vane Pumps

The combination of the high pressure demands on transmission pumps with the established and proven technology of power steering pumps makes the vane pump an excellent choice.

Using a dual-stage ring contour, the vane pump considered here can complete a suction and delivery cycle twice per rotation. This makes the pump very small, predestining it for use as a compact pump in the transmission.

Radially, the gap compensation is achieved through the vanes, which are pressurised.

Axially, both single- and double-sided pressure plate compensation is possible (figure 12).

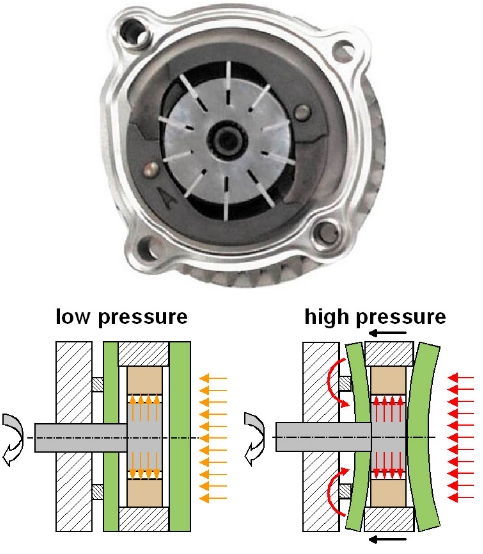


Fig. 12: Gap Compensation in a Vane Pump

At low pressures, the rotor operates between the two pressure plates with axial clearance. The low friction losses allow this system to have excellent hydraulic-mechanical efficiency in the range that is relevant to fuel consumption.

This axial clearance is reduced at higher pressures by deliberate deflection of the pressure plates via the outer pressurised surfaces. This provides good volumetric characteristics, which allow a small nominal displacement, since specification points are in the upper pressure range.

The dual-stage design allows an inexpensive and compact solution for multi-channel flow.

From a hydraulic standpoint, each half of the pump forms a separate pump, which can operate at different pressure levels (figure 13).

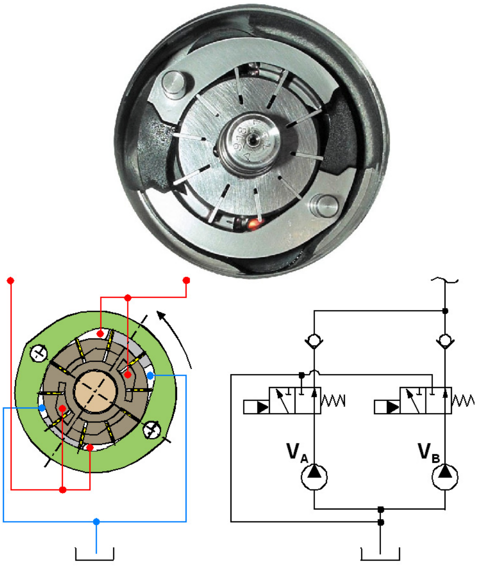


Fig. 13: Dual-Flow Vane Pump – Hydraulic Layout

In the simplest case, one half of the pump can be off loaded and put in circulation at different speeds as needed. The resulting side loads on the rotor are transferred to the shaft by means of a spherical bearing.

Different strokes on the contour ring also allow the pump to be divided asymmetrically. This makes it possible to provide 3 different nominal displacements (V_A, V_B, V_{A+B}) with one dual-flow vane pump. The required switch-over function can often be easily integrated into the transmission control system.

In the speed range that is relevant to fuel consumption, using a dual-flow vane pump allows fuel savings of up to 0.7%. For this to be possible, the pump must be switched, based on demand, to single-channel operation below 2500 min^{-1}.

This pump design offers yet another advantage at maximum vehicle speed. Here, it is possible to save approximately 1600 W of power with a nominal displacement of 14 cm³ and 25 bar pressure. In a medium performance vehicle with a top speed of 200 km/h, this means an increase of 1.6 km/h in the maximum speed with the same engine power. The maximum acceleration also increases by approx. 3%. The effort required to cool the transmission oil is significantly reduced.

The vane pump also has a low kinematic flow pulsation. Special timing grooves or an intermediate capacity ensure smooth pressure transitions leading to lower noise levels.

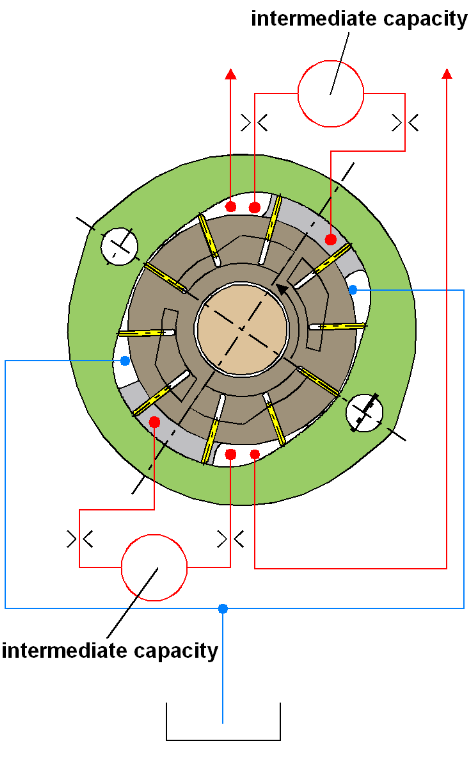


Fig. 14: Use of an Intermediate Capacity with a Vane Pump

The intermediate capacity is a volume that acts like a pressure accumulator due to the elasticity of the aerated transmission oil. Each capacity, in series with two orifices, is set between the chamber to be pressurised and the delivery outlet (figure 14).

LuK Recommendation

Figure 15 shows a concluding, qualitative comparison of the pump principals favoured by LuK, which can be used to discuss the particular respective requirements of the customer.

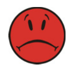
feature	**vane pump**	**internal gear pump**
efficiency		
acoustics / pulsation		
acoustics with highly aerated oil		
cost		
dual-flow pump feasible		
application	**recommended as compact pump (off axis)**	**recommended for torque converter pump hub designs (on axis)**

Fig. 15: *CVT Pump Comparison (High Pressure)*

Summary

LuK has developed hydraulic pumps for many different applications. Their integration in systems with electronic controllers and closed-loop control creates new opportunities for optimisation. The trend toward reducing fuel consumption is taken into consideration by implementing electrical actuation. LuK pumps, which are ready for series production, significantly lower the power requirements of the systems.

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