Development of High Performance CVT Components

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ABSTRACT

Based on the mass produced CVT components for 350 Nm and ratio coverage of 6, the advances of the following LuK components are described: the pulley sets, the hydraulic control with integrated pump and the chain with guide rail. The potential ranges from 400 Nm with the new fully variable torque sensor and optimized chain to 550 Nm and ratio coverage 7 in power split gearboxes. The further investigations on hydraulics and on powersplit hybrid design will also be shown.

INTRODUCTION

A comparison of the recently launched 6-speed automatic and dual clutch gearboxes with the manual transmission gearbox reveals that not all the expectations for these gearboxes in terms of performance and efficiency are met. The 6-speed automatic transverse gearbox for example, exhibits a significantly higher consumption in the MVEG in the order of 12 %, Figure 1. The 6-speed automatic for rear-driven vehicles exhibits, depending on the engine, higher consumptions in the order of 9 %, with decreasing tendency with bigger engines.



Fig. 1: Fuel consumption of AT/DCT/CVT compared to MT

Compared with manual transmissions, consumption with the new dual clutch gearboxes increases by some 7 to 12 %. Only the 3.2 I petrol engine, in comparison to the sportive, short geared, 6-speed manual transmission, can achieve significant fuel savings in the MVEG driving cycle.

By contrast, multitronic[®] [1, 2] exhibits at least neutral fuel consumptions on diesel and an approx. 3% advantage on petrol engines. In terms of combining fuel consumption and comfort, this gearbox continues to represent the optimal design.



Fig. 2: Acceleration of AT/DCT/CVT compared to MT

The primary objective when developing the dual-clutch gearbox was to create a sports "automatic" gearbox and thus improve driving dynamics and driving pleasure. Comparing the acceleration time of 0-100 km/h with those of the manual transmission, we see that despite the absence of a traction interruption, no significant achieved. 6-speed improvement has been The transverse automatic gearbox reduces driving performance by between 6 % and 10 %. The driving performance achieved with 6-speed automatic gearboxes for rear-driven vehicles only approximates that of manual transmissions when combined with powerful engines.

By contrast, multitronic[®] offers the benefit of continuously variable transmission even with less powerful engines

and driving performance approximates that of the manual transmission.

The following features contribute to the impressive performance and consumption values of the CVT components supplied by LuK [6]:

- Chain with low internal losses and high torque capacity with wide ratio spread and low minimal running radii, without limiting the max. vehicle speed;
- pulley sets with LuK double piston principle with the clamping cylinders being directly hydraulically connected and when adjusted, only the small ratio adjustment cylinders are to be operated by the pump;
- hydro-mechanical torque sensor with dual stage response curve modified according to the ratio controlling the clamping pressure at high dynamics without external signals;
- hydraulic control with small number of valves, narrow gaps and small pump with gap compensation.

In summary, LuK believes that the CVT with the structure selected for multitronic[®] represents the best combination in terms of driving comfort, driving performance and consumption. Thanks to the LuK double piston concept, the shift times are limited practically only through the engine's capacity for self acceleration, which, similar to the dual clutch principle, also offers to the ambitious sports driver an adequate solution.

The aim of continued development is to further increase torque capacity and at the same time, further improve overall efficiency by optimizing the components.

VARIATOR DESIGN

Figure 3 shows the variator with primary-side hydromechanical torque sensor.



Fig. 3: Pulley sets with double piston and dual stage torque sensor

The response curve of the dual stage torque sensor is automatically switched between the two different characteristics through the position of the axially moveable sheave by means of opening and closing two bores [6]. The simultaneously employed double piston principle ensures that the outward-lying pressure cylinder of the driven pulley set and the ratio adjusting cylinder on the driving side suffer no leakage which would otherwise occur in the sliding seats.

FULLY VARIABLE TORQUE SENSOR FOR POWER ENHANCEMENT

To further increase the torque capacity to 400 Nm of variator torque, in addition to optimization measures on the chain and on the tribological system of chain and pulley surface, a new type of torque sensor with a fully variable characteristic map curve even over the ratio is being developed [7], Figure 4. Within certain ratio ranges, this torque sensor relieves the chain, the tribological contacts, the disks, the shafts, the bearings, the housing structure and finally also the pressure level for pump, hydraulic control and pressure gaskets. Besides the higher torque capacity, the efficiency of the variator is improved and the power to drive the pump is reduced. The result is further enhanced driving performance and better fuel consumption, as well as a reduced cooling requirement.



- lower loading: Variator, chain, bearings, housing, hydraulies

Fig. 4: Primary pulley set with fully variable torque sensor (VTS)

The key to the functional principle is that the two active ramps of the VTS exhibit variable tangential angles over the radius, Figure 5. These continuously altering angles act over the radial position of the balls, which transfer the torque from the driving to the driven side ramp. The balls are positioned radially in accordance with the actual variator ratio via guiding surfaces, which are arranged on the axially moveable sheave. The desired map curve is created through an appropriate ramp contour and guiding surface configuration.



Fig. 5: Fully variable torque sensor as drawing and exploded view

By integrating the entire ball/ramp mechanism, including ball guides, into the pressure cylinders, the pulley becomes very compact as the length of the moveable sheave is used for the ball mechanism. The initial durability runs at 400 Nm variator torgue have confirmed the endurance capability of the VTS and the associated potential for increasing the torque applicability of the entire CVT system. The achievements of the dual stage torque sensor, such as high accuracy, dynamics and robustness, e.g. with respect to chip tuning of turbocharged engines, remain fully sustained. As an example, Figure 6 displays the measurement with torque jumps on the test rig demonstrating the reliable function, also in respect of the powertrain vibrations occurring with this maneuver as they would in the vehicle with about 100 Nm of dynamic overtorque.



Fig. 6: Measured behavior of the fully variable torque sensor when exposed to fast torque steps

HYDRAULIC COMPONENTS

PUMP CONCEPT

The LuK dual flow vane pump can make a further contribution towards fuel economy. The use of a twostroke ring contour can achieve double take-in / expulsion per revolution. The pump is therefore very small and suitable for an arrangement as a compact pump in the gearbox. In terms of hydraulics, each half of the pump is a pump in itself that can operate at different pressure levels, Figure 7.



Fig. 7: Dual flow vane pump

In the simplest case, one pump half can be switched to low pressure operation as a function of rotation speed. Altering the strokes on the contour ring also allows the pump to be split asymmetrically. Thus, a dual flow vane pump enables three different delivery volumes to be provided: Q_A , Q_B and Q_A+Q_B . The selection function can be integrated into the hydraulic control with small extra effort. When a pump flow is brought onto or eliminated from the system, an abrupt change occurs in the volumetric flow. In order to avoid disruptions in the control pressure, the relevant valves must equalize the change in volumetric flow at high speed by assuming a new operating position.



Fig. 8: Measured switching behavior of the dual flow vane pump

In the measurement shown in Figure 8, one pump flow of approx. 53 bar system pressure is switched over to approx. 3 bar back pressure. This barely affects the system pressure. To prevent toggling when driving within the shift range, a shift hysteresis is also employed.



Fig. 9: Torque of different pump concepts at p=20 bar, T=90 $^{\circ}\!\!\!C,$ Q(1000 rpm) = 10.5 L/min

Figure 9 shows a comparison of various pump principles with regard to torque pick-up over pump speed. All pumps have been standardized so that at a speed of 1000 rpm and a pressure of 20 bar, the delivery rate amounts to 10.5 L/min. In this example, it is assumed that the volumetric flow of 15 L/min is sufficient to supply all functions of the gearbox control with an adequate amount of oil. The most suitable pump must be selected based on gearbox concept, vehicle and engine. The effect of the pump's power draw on maximum engine speed is significant, especially with petrol engines capable of high rpms, and justifies the slight investment in a dual flow vane pump. With a theoretical pump delivery volume of 10.5 cm³ and a pressure of 20 bar, an approx. 1200 Watt saving can be achieved in engine power and at the very end also in cooling capacity.

SLIP-CONTROLLED CLAMPING PRESSURE

Electronic engine control units still fail to provide precise information on current torque and therefore, electrohydraulic claming systems without torque sensor, require for safety reasons a high excess clamping pressure. Using a detection of slip between chain and pulley set, the actually required clamping pressure can be determined and excess clamping can thus be reduced to a minimum.

The algorithm for slip detection pre-supposes that the clamping pressure is modulated [8, 9]. The ideal frequency range for the modulation within which no comfort problems are to be expected and no resonance frequencies occur, is between 20 and 70 Hz.



Fig. 10: Hydraulics for slip-controlled clamping systems with pressure modulation

Figure 10 shows the part of the hydraulic control unit that provides such a clamping pressure system. Low hysteresis, high dynamics, high stability in respect of hydraulic vibrations and high reproducibility of the pressure increase and decrease are the salient requirements. With this hydraulic concept, the modulated clamping pressure is realized using a pressure limiting control valve. The pressure valve is permanently supplied with a volumetric flow, which is never drained to the sump but used for cooling and lubricating the gearbox. The advantage of this arrangement is that the pressure valve, both for the pressure increase and pressure decrease, is always at the same control edge and thus enables high dynamics.

A further aspect is the available volumetric flow. For the pressure increase, the pressure valve closes the control edge and routes the oil supplied by the pump to the pulley sets. As their pressure chambers exhibit a certain elasticity, volumetric flows of up to 10 L/min are briefly required in order to achieve a fast pressure build-up in the pulley sets. As the pressure drops approx. twice the volumetric flow is pumped over the pressure valve to the cooling and lubrication circuits and is therefore retained. The presented hydraulic concept is able to satisfy the dynamic requirements for pressure modulation without the drawback of leakage.



Fig. 11: Test-rig measurement of a slip-controlled clamping system

The left area of the test rig measurement, Figure 11, shows the reaction of the filtered modulated pressure to a change of target slip measure. In the right area, a torque change causes the system to increase the clamping pressure by closed loop control in order to match the constant slip target.

LUK CVT CHAIN

Optimization of the chain performance starts with component design and continues with optimization of the chain assembly. Thanks to highly-developed components and established design procedures, the requirements of a wide range of applications can be satisfied within short periods of time.

CHAIN COMPONENTS

The LuK chain consists essentially of individual link plates and rocker pins. The aim of developing these parts is to create components optimized in terms of both packaging and strength that can still be efficiently integrated into the production process. This complex optimization process requires certain design tools. These include commercial FEM programs and also program extensions for structure or form optimization. However, calculation tools that can cope with the special features of the CVT drive are not always available on the market and specialised software must therefore be developed, e.g. as used by LuK to describe dynamic phenomena. The design tools are completed by the necessary test technology.

Through the consistent application of all available tools, it has been possible to develop an optimized link plate geometry from the current standard production status, which exhibits significant benefits in terms of packaging and strength, Figure 12. Despite an approx. 10 % lower link weight and 10 % less height, it has been possible to significantly increase strength. Chains made from these link plates displayed an increase in strength of approx. $10\ \%$ in the rig test. This new component generation, referred to as the LK 08, is soon coming to mass production.



Fig. 12: Link plate of the chain: comparison between current series and new "light" design

CHAIN ASSEMBLY

The chain characteristics depend not only on the individual components, but also on how these components are assembled to form a complete chain. The key parameters for the chain's strength are the number of link plates in one link and the optimized arrangement of these link plates. Software can be used to find link arrangements that achieve a balanced load on the individual components. This includes a favorable combination between link and rocker pin load.

The measures described above help to create an optimal chain design for the specified application. The modification of existing chain and/or components to suit alternative applications, e.g. [3], results in the chain being composed of many identical components. By altering the composition, the characteristics and installation conditions for the chain can be fundamentally changed with high confidence due to the use of extensively tried and tested individual components.

CHAIN TYPES

However, if the requirements deviate too far from the previous ones, it is advisable to even modify the individual components. In order to expand the application spectrum to smaller torques, LuK is currently developing, besides the aforementioned new link geometry LK 08, a smaller scale link type LK 07. This is based on the described experiences and optimization procedures and permits an even better modification to variators for torques below 200 Nm.

The structured procedure described above enables a wide range of applications to be served within short periods of time in line with requirements. Figure 13 shows how this modular system can be used for various torque categories as a first indication of the chain dimension to be expected. The external conditions, including the collective load, are considered and used to fine tune the chain to suit precise requirements. In addition to the chain widths stated, other intermediate values can easily be prepared on request.



Fig. 13: Recommended chain types for different torque applications (pulley center distance 170 mm, ratio coverage 5.5 ... 6)

SYSTEM-OPTIMIZATION ON POWER-SPLIT CVT AND HYBRID CVT

Power-split gearboxes [7] are a feasible option for torque values of above 400 Nm. The degree to which these gearboxes can be realized, however, also depends on the variator load and specifically the chain tensions and/or stress determined by their structure. Figure 14 to the left shows one beneficial structure of this gearbox design.



Fig. 14: Gearbox structure and resulting variator power load of a power-split CVT.

The power is split at an input planetary gear set into two paths, where depending on ratio the variator has to transfer only 35 ... 70 % of the drive power. This is shown in the right-hand part of the diagram. The driven

side is coupled via one of the two couplings K1 or K2 to one of the two variator shafts, where the outputs then remerge. A reverse gear can be implemented in the downstream gearbox. Unlike similar nonsplit CVT, for such structures a significant torque capacity increase to 550 Nm with simultaneous ratio spread expansion to 7 is expected.

COMBINATION OF POWER SPLITTING, CONTINUOUSLY VARIABLE TRANSMISSION AND HYBRID FUNCTION

For high performance engines, a potential innovative step points towards the hybrid with a small electric motor compared to the capacity of the combustion engine. Figure 15 shows such a structure, on which the electric motor EM has an arrangement that is different to those of conventional starter - generator concepts.



Fig. 15: Gearbox-structure and resulting variator load of a hybrid power-split CVT.

With KB clutch closed, several established hybrid functions including generation, recuperation and boost can be performed with the electric motor. An engine start is also possible if a mechanical minimum clamping of the variator is present and/or the pump is coupled with the electric motor. The electric motor can also be used during transitions between the two infinitely variable operating ranges. In this case, comfort can be improved by feeding the power for the required change of acceleration of internal gearbox rotating masses directly into the gearbox by the electric motor. This allows the tractive power acting on the wheel to harmonise.

In the event of a slipping or open clutch KB, a further additional function is provided by the electric motor when the vehicle is at standstill: If power from the combustion engine is transferred to the electric motor via the planetary gear within the sense of a generator functionality, the planetary gear generates a positive support torque at the gearbox output. This torque can be used with the clutch K1 closed as creep torque or for acceleration in case of consumption-relevant part-throttle move aways. This torque is therefore not generated by friction but is gained by battery-charging without additional energy expenditure. The gearbox thus receives, completely without impacting the variator, an expansion of the move away gear ratio, which could be referred to as generative partial load geared neutral. At higher loads, the drive torque is increased by using clutch KB, whereby the demand-driven and nonhysteresis controllability of the electric motor permits optimized initial acceleration, driving comfort and sportiness.

With such gearboxes, the requirements for "conversion of mechanical power" and "electrical energy storage/supply" are met by distinct technologies. The conversion is primarily mechanical at low cost per kW, low weight per kW and high efficiency of a chain CVT, while the electric motor provides energy storage / supply as its main function and assists the conversion only to a small extent. The consumption advantage achievable in the MVEG alone through elimination of clutch slip under friction torque at standstill and start-up can be in excess of 0.2l/100km.

SUMMARY

Continuously variable transmissions, especially in the structure selected for multitronic[®] with double piston principle and torque sensor, continue to represent the best combination in terms of driving performance and consumption compared with double clutch gearboxes and conventional stepped automatic transmissions.

The newly developed, fully variable torque sensor expands applicability to up to 400 Nm in gearbox structures without power split. The application of the VTS optimizes the clamping characteristic map, which leads to lower loading of the overall system and increases variator efficiency. As an alternative, the illustrated hydraulics enables high-quality pressure modulation for a slip-controlled clamping, which at stationary operating points reduces overclamping to a minimum. The dual flow vane pump reduces the power spent on pump drive, in order to improve the overall gearbox efficiency, especially at high engine speeds.

Thanks to optimized "light" links, chain LK 08 can be used for new applications in higher torque ranges of up to 400 Nm or as chain LK 07 assembled of finer links in the segment below 200 Nm.

The combination of power split CVT and electric motor creates new solutions for cutting fuel consumption in high-performance vehicles with continuously driving comfort.

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