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Smaller, Smoother, Smarter

Advance development components for double-clutch transmissions

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Introduction

The first double clutch transmissions were designed using relatively conventional and controllable wet clutches and hydraulic systems. Using a permanently-operated transmission oil pump where the size and power consumption of the pump is defined by the maximum pressures and the cooling oil requirements of the clutches, leads to losses that affect the fuel consumption in the several percent range. Moreover, the efficiency of the actuation system, in particular the feed through of the hydraulic pressures to the rotating pistons, is directly reflected in the fuel consumption. The first wet double clutches improved fuel consumption compared to the conventional 6-speed automatic transmissions of the time. However, traditional wet double clutch technology does not provide significant advantages over new designs or improved conventional automatic transmissions. Newer developments, such as the VW DQ200 transmission [1], show that double clutch transmissions have the potential to beat manual transmissions fuel consumption performance. The Getrag 6DCT250 [1] proves that efficient electromechanically actuated transmissions are already a reality.

The following discusses the further development of double-clutch transmissions based on this state of the art. This paper shows new transmission components for wet and dry double clutch transmissions and how these components can be combined to form new and more efficient transmission systems.

The dry double clutch with direct actuation

How can the current GETRAG 6DCT250 with electromechanical actuation be further developed? Further reductions in the actuation forces of the clutches and improved wear adjustment system accuracy increase the achievable torques or simplify the mechanical system of the clutch actuation system [2].

A trend towards the compact vehicle market with less than 200 Nm (Figure 2) can be clearly recognized in connection with the discussion about climate change and the current economic status. While the prediction for the average growth of the automobile market is around 20 %, the growth in compact vehicle segments is disproportionally high at 40 %. Therefore compact vehicle segments will achieve a market share of 35 % [3].

For this reason, consideration must be given whether it would be appropriate to scale down a dry double-clutch system suitable for over 300 Nm, or if more appropriate systems are available for compact vehicle applications. In particular, the package as well as the costs plays a significant role in compact vehicle segments. Shorter transmission housings, smaller diameters, and compact transmission shaft arrangements increase the packaging requirements placed on the double clutch and the actuation system.

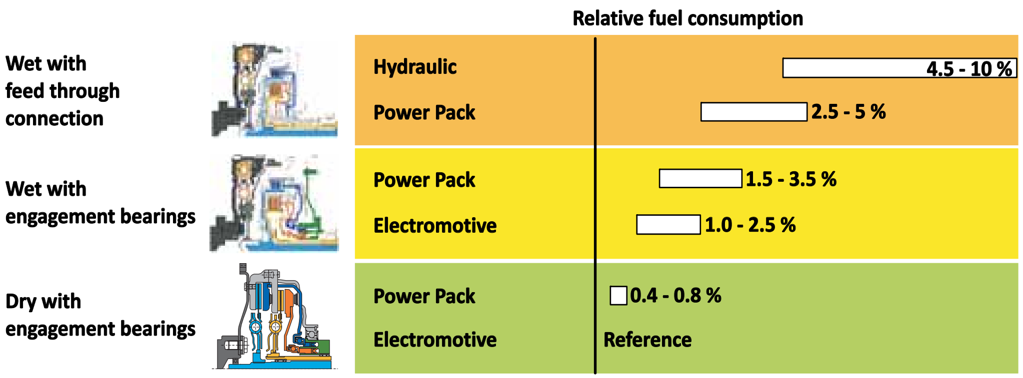

Figure 1 Comparison of fuel consumption (NEDC) of various double clutch systems

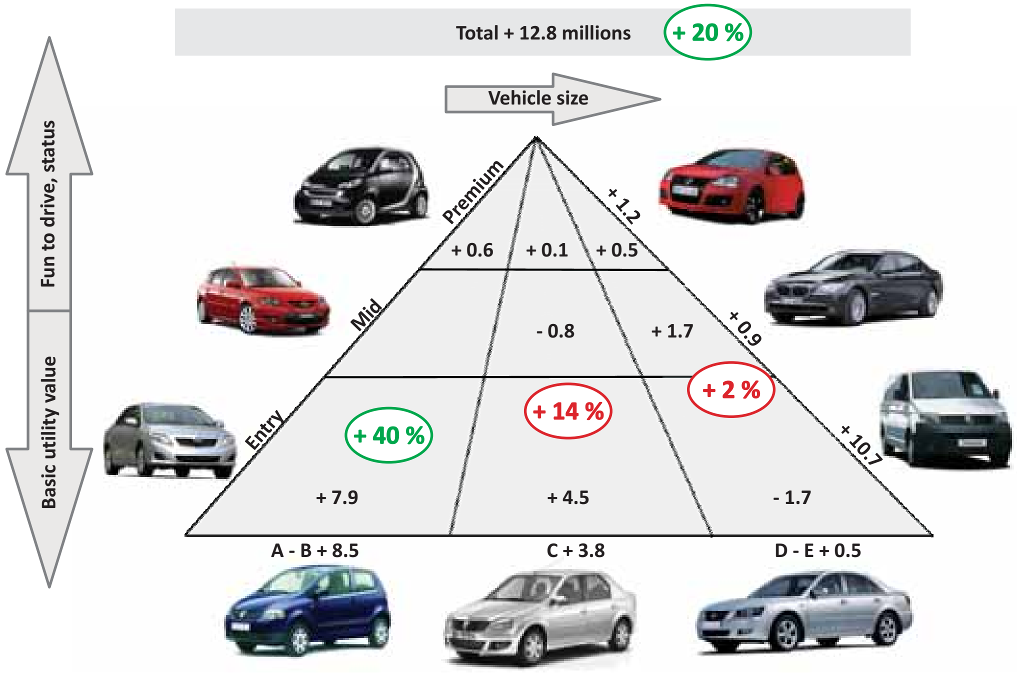

Figure 2 Size of vehicle segments in 2015 compared with 2007 in millions (from CSM database)

LuK has therefore researched "how much clutch" is required in this critical space and has further analyzed the structure of the double clutch.

Elimination of force ratio and wear adjustment

A high force ratio in the clutch reduces the actuation forces on the engagement bearings, however the package required due to the longer actuation travel and the lever spring motion is increased. A high force ratio is therefore eliminated for low torques allowing a more compact package. The maximum engagement forces to the clutch are now determined by the engagement bearing capability. It is therefore important to consider realistic load and temperature ranges when designing these bearings. If, due to dynamics, the clutch torque tracks the engine torque, lower bearing forces are generated than when the clutch is fully engaged [4] [5]. Around 170 Nm maximum engine torque is possible depending on the design.

The wear adjustment system can be omitted, since the wear distance on the clutch linings is also no longer increased by the force ratio. This means that several components can be omitted in the double clutch, significantly reducing required package space.

A design with four plates was selected in order to simplify the system. What remains is a clutch in which the forces introduced in the engagement bearings are directly transmitted to the clutch linings via a cup-shaped element. LuK therefore calls these clutch concepts directly-actuated clutches (Figure 3).

Bearing supports, offset compensation and force compensation

The following aspects must be considered when defining the bearing supports for the directly-actuated double clutch:

- The unavoidable radial offset between the engine and transmission must be compensated.
- The forces, torques and movements that occur in the clutch system interfaces may not lead to

complex interactions such as judder, torque modulation or torque transfer noise.

- If possible, supporting high loads on the engine or transmission side should be avoided.

The engagement system integrated into the clutch cover can follow the axial and angular motions of the clutch without modulating the clamp load of the clutch. A double concentric slave cylinder that has two concentrically arranged pistons is used as the engagement system. The forces generated by hydraulic pressure are supported by the engagement bearings and by the clutch 1 and clutch 2 cover bearing. Since the flow of axial forces is closed through the clutch lining, axial support on the crankshaft, housing or one of the transmission input shafts is not necessary. This is providing a further advantage for integrating the double clutch into the transmission.

Variants of the directly-actuated double clutch

Figure 3 shows a variant of the directly-actuated double clutch with damped disks that is dimensioned for most engines in the compact vehicle segment.

The double clutch is positioned by a flexplate on the crankshaft and supported by bearings on the transmission side in order to compensate the offset between engine and transmission. The entire assembly can adjust itself to the offset between the crankshaft and the transmission input shaft. The offset between the double clutch and the transmission input shafts is compensated in both damping elements of the clutch disks.

Figure 4 shows the modified variant with a dual mass flywheel (DMF). Here, the double clutch is

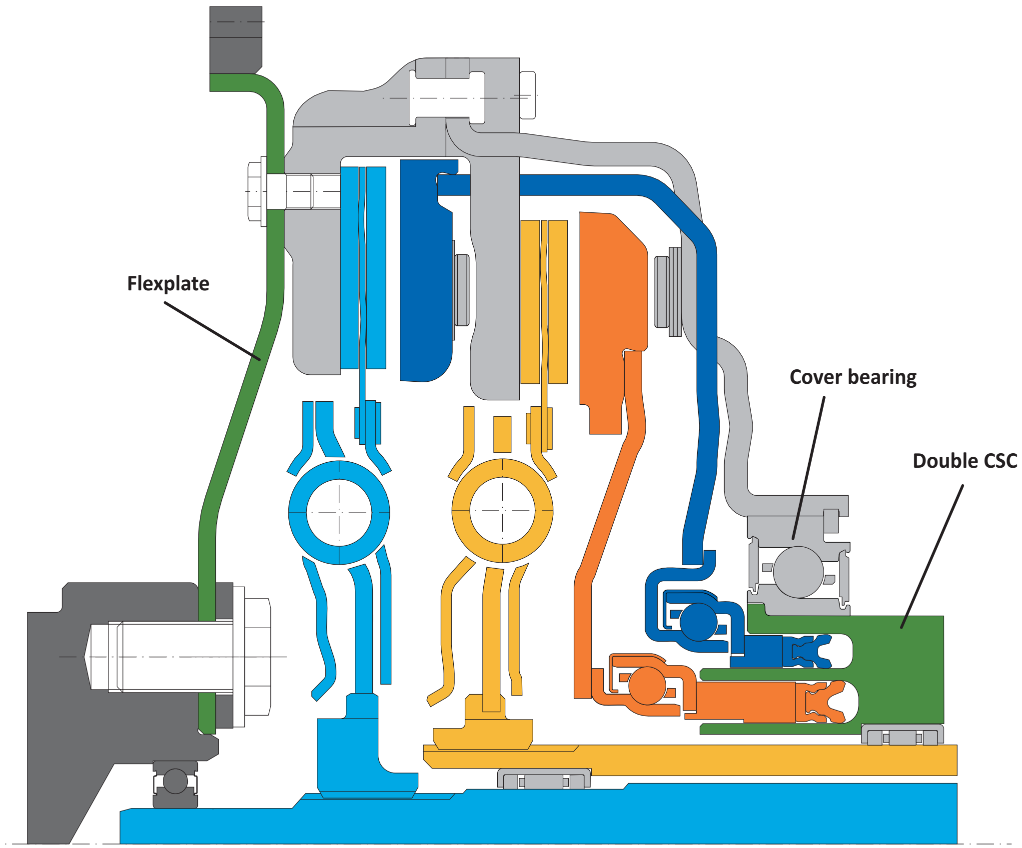

Figure 3 Directly-actuated double clutch with damped disks

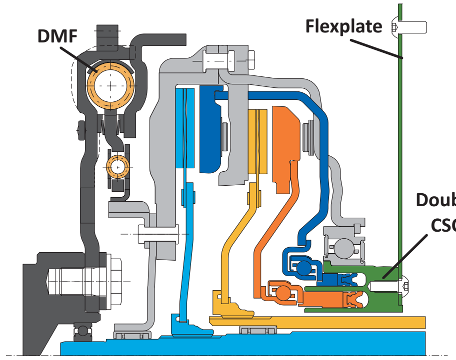

Figure 4 Directly-actuated double clutch with dual mass flywheel

positioned above a non-rotating flexplate on the transmission side and supported by bearings on the crankshaft side. The system can compensate for the radial offset as well. The double clutch is driven by the preloaded spline between the dual mass flywheel and the double clutch. The variant with a DMF is beneficial especially for three and four cylinder engines with very high excitations.

Figure 5 shows a variant derived from Figure 3 with an additional centrifugal pendulum for eliminating the engine excitations. Since the natural frequency of the dual mass flywheels in two and three cylinder engines moves towards higher speeds, isolation at lower speeds is not possible. Therefore a centrifugal pendulum on the primary side can be more effective with such engines then a DMF [6].

Other variants, particularly other combinations of the above damping elements, are feasible. This

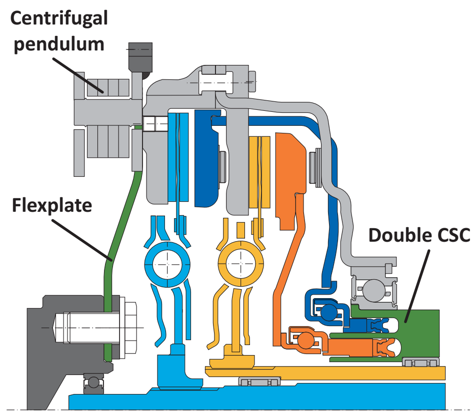

Figure 5 Directly-actuated double clutch with damped disks and centrifugal pendulum

means, for example, that a DMF could also be combined with damped disks or with a centrifugal pendulum.

Summary for dry double clutches

The development of the dry directly-actuated double clutch yields a clutch system that fulfills the requirements of compact vehicle segments in particular. Reduced to the most important components, the system presents the optimum in terms of package and costs. The clutch can be actuated both via a conventional hydraulic system or a power pack by means of the double concentric slave cylinder. Efficient electromechanical actuation can be used by means of a hydrostatic connection.

The dry directly-actuated double clutch represents an additional core component now available to manufacturers of double-clutch transmissions with no compromises in terms of fuel consumption.

Wet double clutches

Wet clutches, cooled with oil, are most suitable for passenger vehicle applications with more than 300 Nm of torque. More space is required within the transmission itself to realize the higher torques, which means that the available space for the clutch is smaller. Since sufficient thermal capacities can no longer be installed, oil cooling and an external actuator must be used. However, using a wet double clutch can also be beneficial with lower engine torques if the startup ratio or high vehicle weight lead to high clutch energy.

As mentioned, wet double-clutch transmissions are inferior to dry clutch transmissions in terms of fuel consumption in most cases. However, as with dry double clutches, the potential for improvement of wet double clutch systems exists. A fuel consumption comparison to a dry electromechanical double-clutch transmission can be very close, if the wet system is also consistently optimized. The demand-controlled cooling pump independent to the clutch actuation is critical for improved consumption. Another key is the minimization of losses in the actuation system. Here in particular the feed through of the hydraulic pressures to the rotating pistons must be optimized. The hydraulic and frictional losses of the seals can amount to over 100 W, even in partial load operation.

Actuating the wet clutch via the engagement bearings and double concentric slave cylinder means that these permanent losses are omitted.

Figures 7 and 8 show wet double clutches that are each activated by means of a double concentric slave cylinder via engagement bearings. The life of the bearings is not limited by the grease operating life as the bearings are lubricated with gearbox oil and can therefore be subjected to higher loads. Similar to the dry directly-actuated double clutch, supporting the engagement forces within the clutch by means of a bearing secured on the cover is advantageous. After defining the most efficient boundary conditions, different designs can be developed by varying the torsion damper and creating the best possible package.

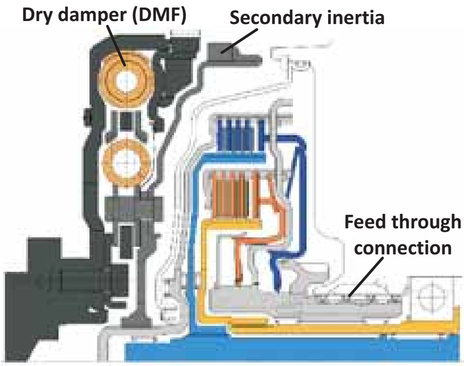

Figure 6 Conventional wet double clutch with feed through connections to the rotating pressure pistons

Figure 7 shows a conventional dry DMF located before the clutch unit. Since a wet clutch has a low inertia in comparison to a dry clutch, additional masses must be installed in order to achieve a comparable isolation.

Figure 8, on the other hand, shows a system where the torsion damper and a centrifugal pen-

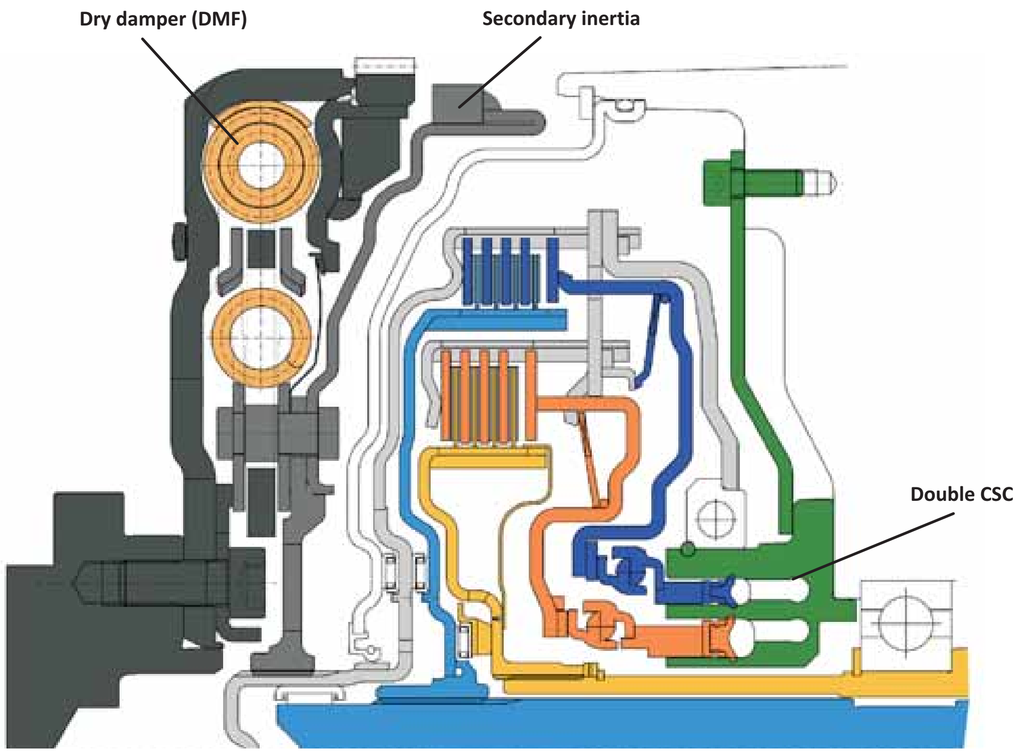

Figure 7 Wet double clutch with double concentric slave cylinder and dry DMF

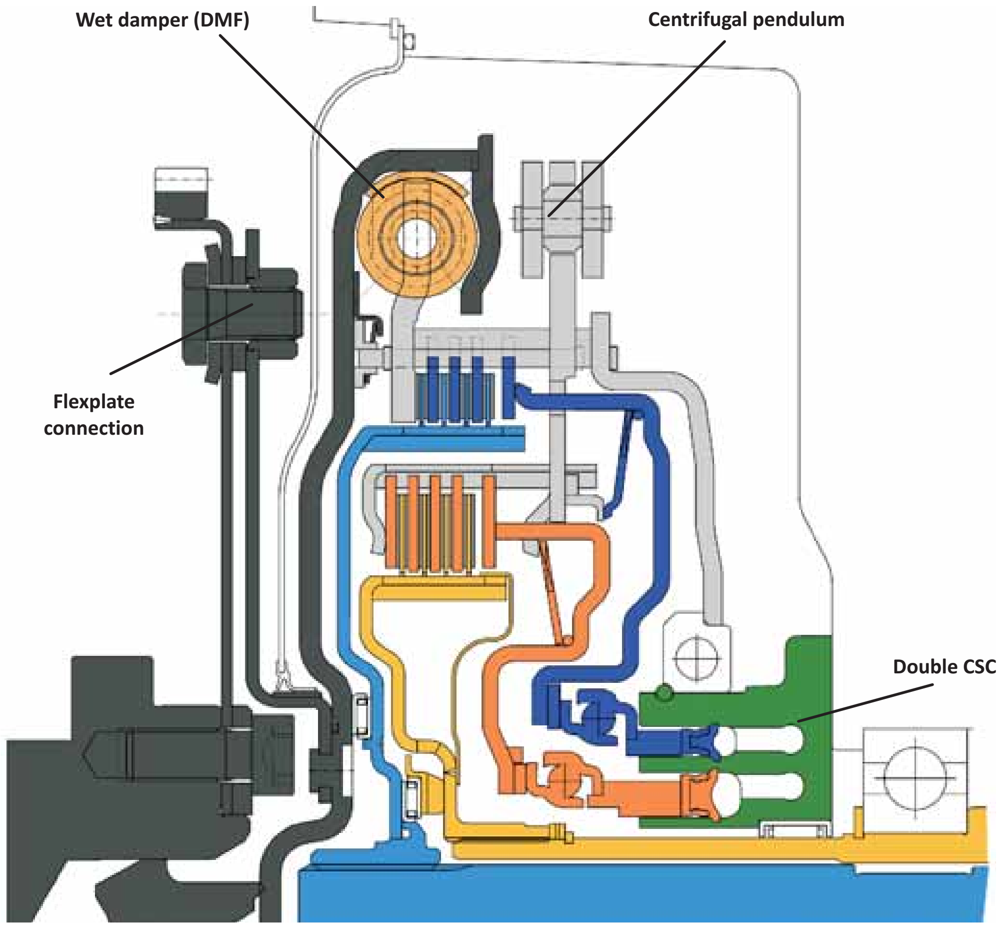

Figure 8 Wet double clutch with double concentric slave cylinder and integrated torsion damper and centrifugal pendulum-type absorber

dulum-type damper have been integrated into the oil chamber. Here, the centrifugal pendulum generates the isolation effect of a large secondary mass with considerably less weight. Together with an arc spring damper yields better isolation than compared to a DMF. The improved integration of wet clutch and damper results in reduced demand on axial package requirements in some cases. The oil lubrication required by the torsion damping elements is also beneficial in terms of wear and function.

As in current automatic transmissions and CVT's, abraded clutch lining and metal particles from worn interfaces remain in the cooling oil circuit and transmission. This must be considered when designing a hydraulic system optimized in terms of leakage and oil operating life. However, arc spring dampers have considerably lower wear in the oil chamber compared with competitors' concepts. Furthermore, an actuator independent of the cooling oil circuit, such as an electro-mechanical system or a power pack, is even more effective.

Summary for wet double clutches

Actuating the wet clutch via a double concentric slave cylinder with engagement bearings results in a significant advantage in terms of efficiency, namely by eliminating the feed through of the hydraulic pressures to the rotating pistons. Wet clutches can be actuated by a conventional transmission hydraulic system and a power pack

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by means of the double concentric slave cylinder. Efficient electromechanical actuation can also be used by means of a hydrostatic connection.

The directly-actuated wet double clutch and the relevant damping elements represent a further core component now available to manufacturers of double-clutch transmissions with no compromises in terms of fuel consumption.

Smarter with local control units

In the case of double-clutch transmissions, the failure mode (which must be defined as a safe mode) is activated through a total electronic failure. The failure results in zero actuation pressure and both clutches open. However, this is not optimal in all respects; especially in comparison to conventional automatic transmissions which can be operated in “limp home programs” in the case of a total failure of the electronic system.

The two independent sub-transmissions in a double-clutch transmission form an excellent basis for an effective limp home function. Thereby the system availability is improved even when components are only partially available. Modern double-clutch transmissions are already using such possibilities to a certain extent today; however the function of the central electronic or hydraulic transmission control units remains critical. If the central control unit fails, the system enters the safe mode “clutch open” and the vehicle remains stationary.

In order to achieve comparable behavior for the 6DCT250 (actuated using EC-motors), a self-opening function was included in the requirements of the clutch actuator system [1]. This requirement alone has far-reaching consequences on the design of the clutch and actuator system. For the clutches, enough return force must be supplied at any time such that the actuator can be forced into the initial position within a defined time. When designing the clutch, the counterforce must be taken into account as an offset to the actuating force. The counterforce is therefore lost respective to clamp load for the clutch linings.

To reduce the lost force, the actuator must offer the lowest possible mechanical and electrical resistance. This places high requirements in terms of mechanical efficiency on the operation of the spindle screw drive and, in parallel, the peak torques incurred through impacting the actuator end stop must be minimized. Such requirements lead to a mechanical design with stronger bearings or by using a torque fuse to allow the spindel screw to slip when an impact occurs. Accordingly, the requirement for self-opening is a high hurdle for electromechanical clutch systems that must be met with the relevant additional design.

Extensive consideration was given to this “safe mode” in order to increase the vehicle availability, and to reduce the special requirements placed on the clutch and the clutch actuator.

Non self-opening clutch systems

The current state of the art defines that a single faulty clutch in the drivetrain can be controlled by the driver, regardless of clutch fail-safe operation: open, stationary, or closed. In manual transmissions and in automated manual transmissions, this is accepted as safe in the field today [7].

When applied to double-clutch transmissions, if one of both clutches can be opened quickly enough during a failure, the transmission behaves like a manual or automated manual transmission (ASG) and can be controlled by the driver. Therefore if both clutches can be controlled independently of each other, the self-opening behavior during failures can be omitted entirely. Nevertheless, a sufficiently quick clutch failure detection and reaction time must be ensured.

The local control unit (LCU)

The objective was to define an independent intelligent electronic system for each clutch without generating disadvantages such as additional package requirements or costs.

The printed circuit board, required currently for detecting EC-Motor position, is replaced by a new control unit. A 16-bit microcontroller is managing the communication with the superordinate control system via the CAN-bus, the recording of input signals and contains software functions related to the actuator.

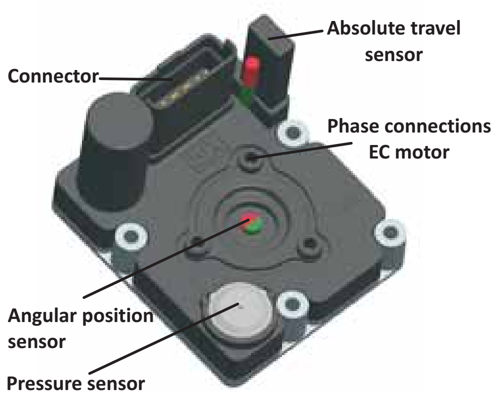
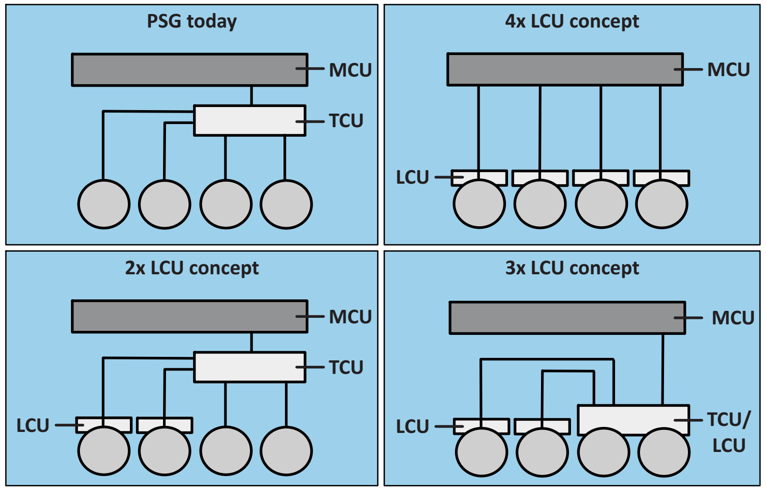


Figure 9 Local control unit (LCU)

The sensor system consists of the rotating shaft measurement system and a temperature sensor. Additional sensors can be added if required. The control unit circuit board is completed by EC-Motor commutation, EMC-Filters and a monitoring controller. Finding suitable components and arrangements that matched the temperature and vibration conditions in the transmission environment and fitting them into the available space was particularly challenging in the project.

As mentioned, it is useful to make the clutch actuation system separate from the central transmission control unit. That the local control units each have their own independent power supply is also important. The additional design required for the control units is compensated by simple connectors and smaller wiring harnesses. If the motors for transmission actuation are also equipped with local control units, the conventional transmission control unit can even be omitted entirely. The coordinating software is then integrated into an existing control unit such as the engine control unit, thereby leading to cost savings over previous systems with central control units. The utilization of local control units also facilitates new system architecture variants. Figure 10 shows some of these variants.



MCU - Master Control Unit
TCU - Transmission Control Unit
LCU - Local Control Unit

Figure 10 System architecture with local control units

Summary for local control units

The developed local control unit provides a technology that breaks new ground in terms of system architecture. The system can be further enhanced when combined with an electromechanical transmission actuation system, such as the LuK Active Interlock actuator [7] [8]. Non self-opening clutches and even self-closing clutches are then also permitted in the system design. Through the improved system architecture, the clutch and actuation mechanism can be greatly simplified.

Electromechanical gear and clutch actuation have an average power consumption of approximately 20 W, which is hardly relevant for fuel consumption and represents the current benchmark. The new local control units significantly reduce the power consumption even further.

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The LCU in clutch and transmission actuation represents a new component now available to manufacturers of double-clutch transmissions with no compromises in terms of fuel consumption, safety and vehicle availability.

The hydrostatic clutch actuator (HCA)

Semi-hydraulic activation of the clutch using a hydrostatic section has been the state of the art in manual transmissions for many years. The clutch pedal activates a master cylinder that pushes down on an oil column that, in turn, moves the slave cylinder on the clutch thereby actuating the clutch. The clutch pedal has already been replaced by an electromechanical actuator system, which performs an automated clutch actuation function in several volume production projects (electronic clutch management – ECM). LuK has successfully and reliably implemented, and continues to implement this technology in several ECM and ASG applications [4] [7]. The new system architecture design options mentioned above enable this proven technology to be implemented in double-clutch transmissions.

HCA design

The first prerequisite for this system is a double clutch with slave cylinders such as the directly-actuated dry and wet double clutches mentioned above. When designing the actuator system, the realization and location of the extremely high ratio from the clutch lining clamp load to the electric motor torque is of great importance. If the ratio is implemented in the clutch (lever spring), for example, the force level in the section to the actuator is reduced, but the stroke is increased. When a variant is selected, checks must be made how the force levels and required stroke travels at different points affecting the system (Figure 11).

The piston surfaces in the slave cylinder can be defined out of the maximum permitted pressure and the maximum permitted forces on the engagement bearings. A compromise must often be found here due to the lack of space. The electric motor characteristics (maximum speed, maximum torque and positioning accuracy) are defining the total ratio to be realized. In principle, two ratios are already available for implementing this total ratio. The first is the ratio of the hydrostatic section that is defined by the relationship of the piston surfaces from slave to master cylinder. The second is the transmission ratio that converts the rotary motion of the motor shaft into a linear stroke motion. No additional ratio should be provided due to costs and efficiency. Calculations show that a compact actuator can only be produced with a large transmission ratio in the spindle drive of maximum 1 mm per revolution and a moderate hydrostatic ratio less than 3.0. Therefore new approaches in the spindle drive are necessary. The details of the design can only be defined through an iterative simulation process.

Design

The low spindle pitch is implemented by means of a planetary roller spindle that has previously been used in aerospace and industrial applications [9] [10]. A cost-effective solution suitable for automobiles is being developed in conjunction with INA, while the components are mostly manufactured by forming methods. It was possible to arrange the large piston surface of the master cylinder radially around the spindle, minimizing section length. The piston is designed as a traction piston in order to efficiently transfer the high axial forces from the housing to the spindle bearing support. A so-called reset position is provided when the clutch is open. In this position, the pressure line is connected with the reservoir such that changes in fluid volume caused by temperature can be compensated. The spindle is driven by an EC-Motor in the actuator with the local control unit described.

Sensor system concept

The angular position of the rotor must be sensed such that motor commutation can occur. The field of the magnet located on the spindle is evaluated by an angular position sensor located on the circuit board. The mechanical setting between the stator and sensor position is therefore omitted, providing a more accurate and cost effective solution. An integrated temperature sensor helps to protect the output stages.

At maximum motor current, the HCA can generate high forces far above normal operating levels due to the large ratio. To prevent all components from over-design, a sensor system concept was defined that ensures the safe function of the actuator system with a relatively low amount of ef-

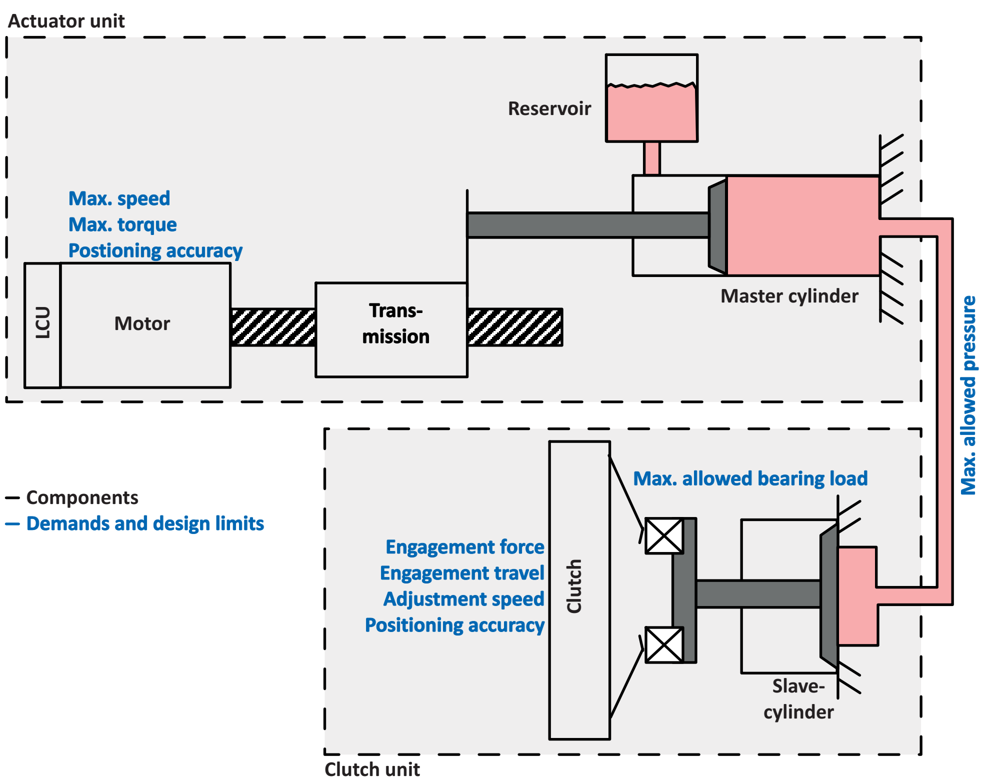


Figure 11 Hydrostatic clutch actuation system

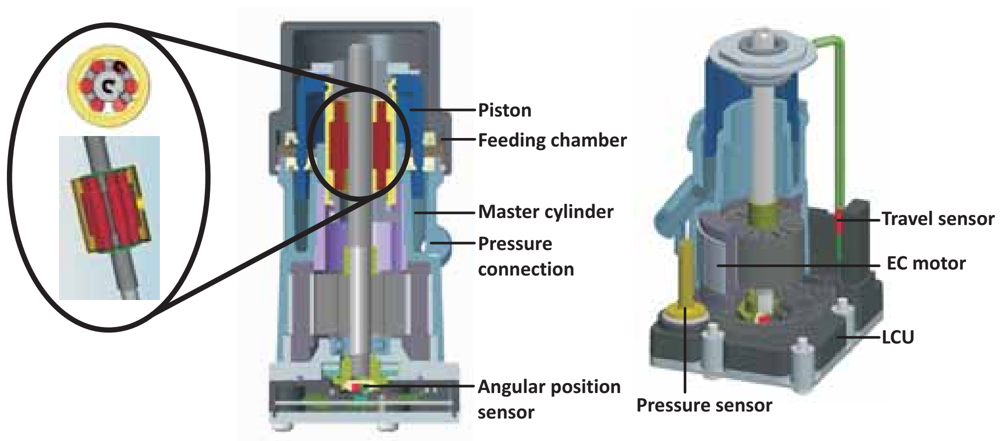


Figure 12 Hydrostatic clutch actuator

Components for double clutch transmissions 11

fort. A pressure sensor serves as overload protection for the hydrostatic section and the clutch. The signal can also be used to reliably measure the clutch characteristic curve, even if no gear has been selected. The variability of the hydrostatic section, due to the thermal expansion of the fluid, for example, can be detected and accounted for by the software. An absolute position sensor is provided in the actuator for measuring the piston position.

Using the local control unit mentioned above and locating all sensors near to the circuit board yields a cost effective system through minimized wiring and connectors.

Summary for HCA

The new HCA is a further high-performance component for automated clutch activation. Due to the comprehensive optional equipment, the HCA can be adapted for various applications. Furthermore, it is possible to scale the components for the selected design. Along with double-clutch transmission applications, the system can be used as a single actuator for clutch-by-wire applications or for the operating of hybrid clutches. The local control units provide a simple interface to the vehicle and to other systems. Numerous possibilities can be implemented if the actuators are arranged in the engine compartment. Two actuators can be integrated in a single housing and can also be connected to single or common reservoir. The actuator system has been designed in such a way as to facilitate locations to the transmission, engine or chassis. Thereby all prerequisites for a wide variety of applications in clutch actuation have been fulfilled.

Overview of components

Two new double clutch types, a local control unit and a new actuation system have been presented in this paper.

When reduced to its most important components, the directly-actuated dry double clutch represents the optimum with respect to package and costs, and is particularly suitable for low engine torques in the smaller vehicle classes.

Actuating the double wet clutch using a double CSC with engagement bearings results in a significant advantage in terms of efficiency, namely by eliminating the feed through of the hydraulic pressures to the rotating pistons. Thereby wet double clutches can also be combined with more efficient actuation systems.

Using the local control units the clutch systems must not be self-opening anymore. Through the improved system architecture, the clutch and actuation mechanism can be greatly simplified. As well systems with the electromotive lever actuators could be improved due to this technology.

As a second efficient clutch actuation a new hydrostatic clutch actuator was presented. Equipped with local control units and optional sensor systems, various double and single clutches can be automated, for example, for hybridization.

This new components are generating, in conjunction with the further development of well-known components, a high modularity (Figure 13). This is enabling transmission manufacturers to find customized solutions for individual applications. All presented new solutions have one common trait: no compromises are made in terms of fuel consumption.

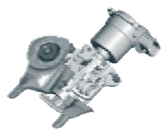
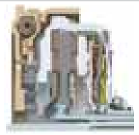
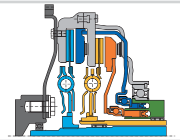
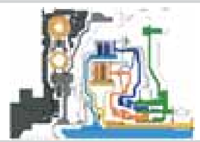
Clutch types and actuators		Electrohydraulic actuator “Power pack”	Electromechanic actuator “Lever actuator”	Hydrostatic clutch actuator “HCA”
				
Dry double clutch with wear adjustment		✓	✓	✓
Direct dry double clutch		✓		✓
Wet double clutch		✓	✓	✓

Figure 13 Clutch types and actuator systems

Literature

[1] Kimmig, K.; Bührle,P.; Henneberger, K.; Ehrlich, M.; Rathke, G.; Martin, J.: Success with efficiency and comfort – The dry double clutch has become established on the automatic transmission market; 9th Schaeffler Symposium, 2010

[2] Reik, W.: Less is more! Using unconventional means to design new products; 9th Schaeffler Symposium, 2010

[3] Forecast of vehicle production 2007-2015, CSM worldwide database, January 2010

[4] Fischer, R.; Berger R.: Automation of Manual Transmission, 6th LuK Symposium, 1998.

[5] Wagner, U.; Bührle, P.; Müller, B.; Kimmig, K; Kneissler, M.: Dry double clutch systems – Innovative components for highly-efficient vehicle transmissions, ATZ 11/2009, pp. 826-833

[6] Kroll, J.; Kooy, A.; Seebacher, R.: Land in Sight? Torsional vibration damping for future engines; 9th Schaeffler Symposium, 2010

[7] Pollak, B.; Kneissler, M.; Esly, N.; Norum, V.; Hirt, G.: Electro-Mechanical Actuators – Shifting Transmissions Into Gear, 7th LuK Symposium, 2002

[8] Wagner, U.; Berger, R.; Ehrlich, M.; Homm M.: Electromotoric actuators for double clutch transmissions – Best efficiency by itself; 8th LuK Symposium, 2006

[9] Dietrich, J; Gombert, B.: Device for converting rotary movement into axial movement; Patent EP000000320621B1, 1988

[10] Balázs, M.: Analyse und Modellbildung einer Planeten-Wälz-Gewindespindel, München, Technische Universität, Dissertation, 2000