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Success with efficiency and comfort

The dry double clutch has become established on the automatic transmission market

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Introduction

Since VW launched the first automatic transmission with a dry double clutch in the Golf class at the beginning of 2008, a large number of drivers and automotive experts have experience with this technology. The system is earning high ratings in various publications and comparative analyses. It meets and even exceeds the expectations in terms of driving characteristics and fuel consumption.

As the issues of fuel consumption and environmental protection are gaining more importance worldwide, the dry double clutch transmission (DCT) has established itself in the strongly growing automatic transmission market along with wet DCTs, CVTs and advanced torque converter transmissions. Given the current intensive development activities of vehicle manufacturers and suppliers, significant increases in the number of dry double clutch applications in the next few years is expected, especially in the mass market for lower mid-size and compact class vehicles. After VW, transmission manufactures Getrag and Fiat Powertrain Technologies (FPT) have developed DCTs for production, and in the last few months introduced them to the market in collaboration with automotive manufacturers Renault, Ford and Fiat.

Shown in Figure 1, are the predicted production quantities of different automatic transmissions, especially of the dry DCT.

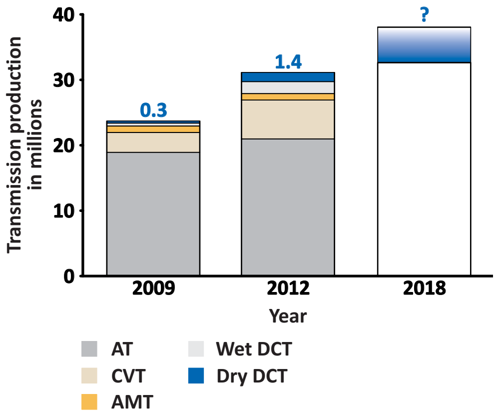

Figure 1 Expected development of the quantities of dry double clutch applications and automatic transmissions

Description of dry double clutch transmissions

At the beginning of every development of a new dry double clutch application, answers to crucial questions about system design are determined by means of suitable system simulations. Simulations include the number of gears and the gear ratios of the transmission, the size and weight of the double clutch for matching the system's thermal robustness and operating life, and the characteristics of the required vibration damping elements such as dual mass flywheel dampers and/or clutch disk dampers. Analyzing these factors in conjunction with the relevant control strategy must not only include the clutch controls but also the engine and transmission controls as an overall system. Previous publications [5], [6] describe important elements of such system simulations. Descriptions of the parameters and requirements of the systems are continuously refined based on the experiences of different production automotive applications.

Using the term "dry double clutch system" today, gives no uniform concept as to the specific double clutch, double clutch actuator and transmission actuator used. Various concept studies and production development activities during the last few years have shown that there are several practical combinations of a dry double clutch with an associated clutch and gear actuation system. These combinations can vary according to the system as shown in Figure 2.

A practical and proven variation is the combination of a dry double clutch with an electro-hydraulic clutch and transmission actuation system. VW is the pioneer of this technology with the seven-speed DCT DQ200, which has been on the market since the beginning of 2008.

Dry double clutch for DCT with electro-hydraulic actuation system

Figure 3 shows the basic design and the system components of the VW seven-speed DCT DQ200.

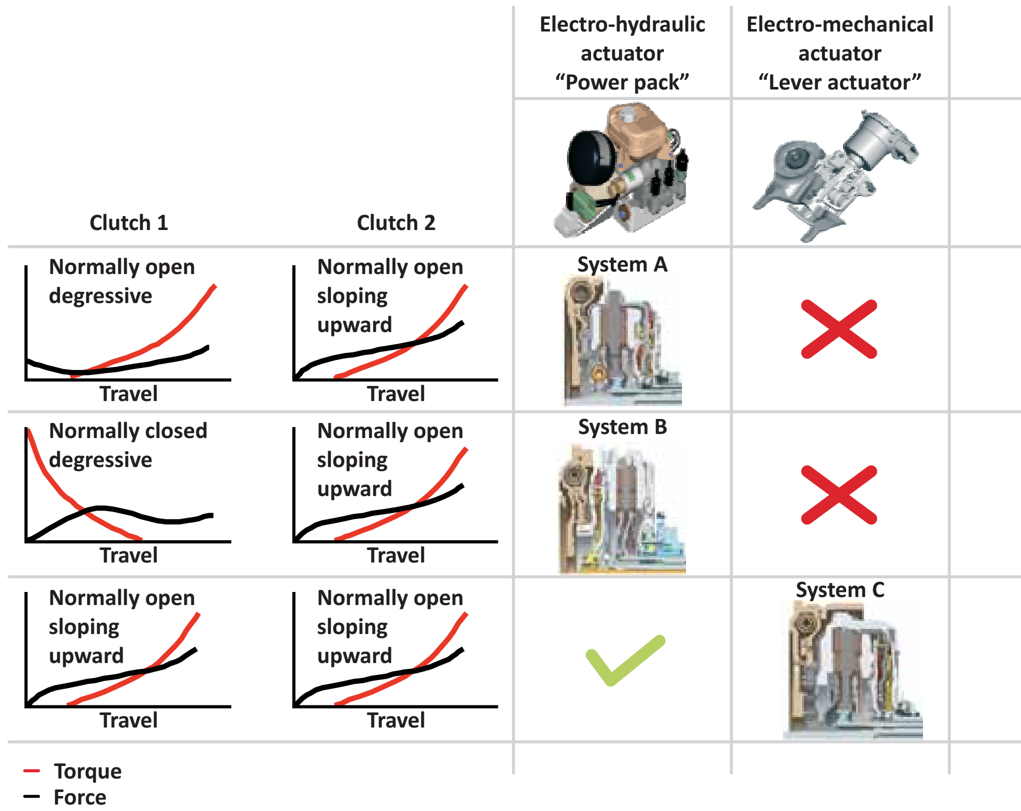

Figure 2 Combinations of dry double clutches and actuators

This transmission uses a double clutch with two normally open clutches with independent wear adjustment systems. The two clutches require minimal space due to the use of wear adjustment systems with force sensors, which is similar to many manual clutches [1], [6]. A special feature of this double clutch is that the two clutches have different force-travel characteristic curves. The force curve of clutch 1 for odd-numbered gears has a downward slope. In contrast, the characteristic curve of clutch 2 for even-numbered gears permanently slopes upward (Figure 2, System A). The differences in the characteristic curves are due to the type of wear adjustment system and the geometrical clutch arrangement. In general, downward force-travel characteristic curves as those of clutch 1 are optimal as this leads to a higher inherent efficiency of the clutch. However, actuation for such systems can only perform by means of an actuator with travel control.

External actuation plungers of the electro-hydraulic power pack transfers the actuation force to the lever spring fingers of the double clutch by means of a nested lever system with a specially matched flexible connection and compensation function [4]. The actuation system requires a flexible connection in order to prevent interferences caused by static and dynamic errors from exceeding a threshold value. Control of the Clutch is via the hydraulic plungers that use a travel control system with travel sensors on each plunger.

A special feature of the system is a support bearing which retains the double clutch axially and radially on the hollow shaft. This allows the crankshaft to be free from the actuation forces and the mass of the double clutch since the clutch connects non-rigidly with the crankshaft via a flywheel. The most significant advantages are reductions in the axial and bending vibrations applied on the crankshaft.

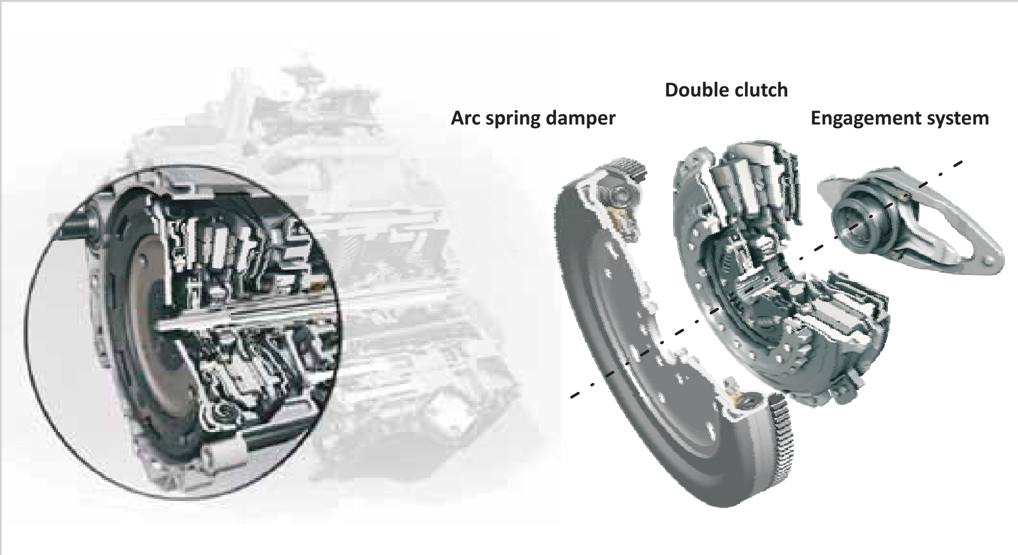

Figure 3 Double clutch system of the VW seven-gear DCT DQ200

Another advantage of this design is that the complete double clutch system can be assembled ready-for-use and tested as an overall system at the transmission plant. In the DQ200 DCT and with many other dry DCTs, the double clutch on the transmission side connects the flywheel arc spring damper on the engine side by means of preloaded spline teeth. The preload completely prevents gear noise caused by the alternating torques of the engine. The floating damper flange of the grease-filled arc spring damper easily compensates for the axis offset between engine and transmission.

Another DCT with a dry double clutch and electro-hydraulic clutch and transmission actuation is the C635 from FPT. This transmission is a six-speed DCT with a torque capacity of up to 350 Nm.

The clutch housing of this type of transmission has only very limited space available for the double clutch. The double clutch is therefore designed so that clutch 1, on the engine side, is actuated by means of a pull rod in the transmission input shaft and a small hydraulic cylinder on the transmission side. Activation of clutch 2 on the transmission side is by means of a concentric slave cylinder (CSC, Figure 4) in a similar manner to many manual transmissions.

This specific actuation concept allows the double clutch to be firmly located on the transmission housing using a flanged bearing, which in return leads to space advantages. A new feature of this double clutch is that both clutches are not normally open. Clutch 1 is normally closed as this is the case for a standard clutch, which allows the use of a clutch with wear adjustment (SAC) for minimizing the characteristic curve variation and the actuation forces [9]. Clutch 2 is normally open and has no wear adjustment, which leads to an increased total actuation travel but significantly reduces system complexity (Figure 2, System B).

This clutch design requires a matched safety and monitoring concept for preventing undesirable stresses on the transmission in every driving situation. This double clutch system also uses an external arc spring damper with preloaded spline engagement teeth for dampening torsional vibrations in both gasoline and diesel engines.

Dry double clutch for DCT with electromechanical actuation system

Established in the market during the last few months are systems with electromechanical clutch and transmission actuation along with the DCTs with electro-hydraulic clutch actua-

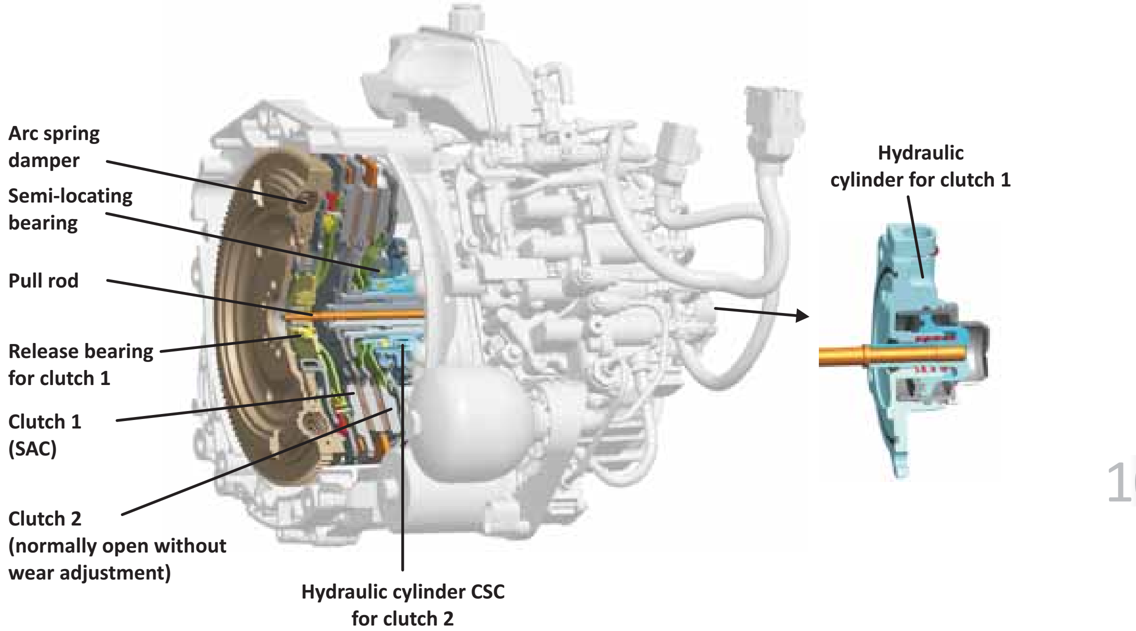

Figure 4 Double clutch system of the FPT (Fiat Powertrain Technologies) six-speed DCT C635

tion. The first production transmission with this technology is the 6DCT250 from Getrag. This DCT uses a newly developed LuK lever actuator for actuating the double clutch. The lever actuator contributes to the extremely high total efficiency due to low losses in the electromechanical system and can be integrated in the clutch housing with nearly no effect on the design envelope due to its compact design (Figure 5).

The system safety requirements specification demands two normally open clutches. A lever actuator and a matched clutch characteristic curve (continuously sloping upward) meet this requirement (Figure 2, System C). To achieve the desired transmission torque capacity of 280 Nm with this a highly-efficient and compact actuator, a double clutch with high-precision wear adjustment based on travel sensors was specially developed for the application (Figure 8).

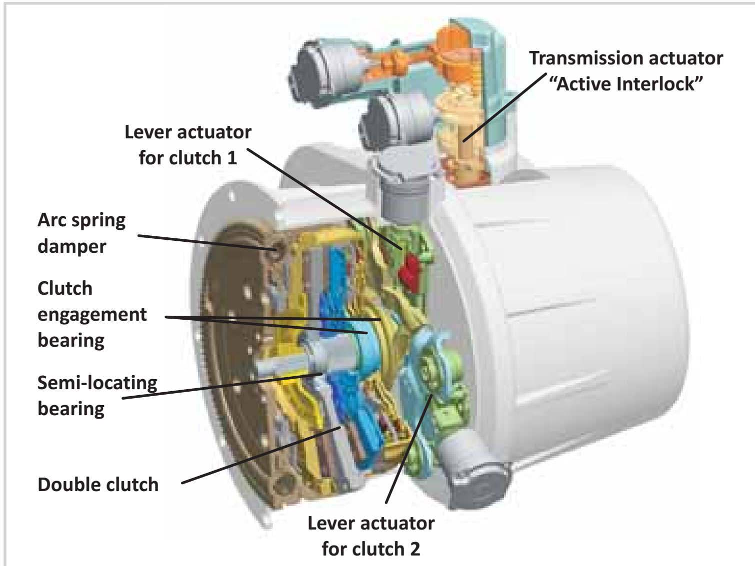

Figure 5 Double clutch system with electromechanical clutch and transmission actuation

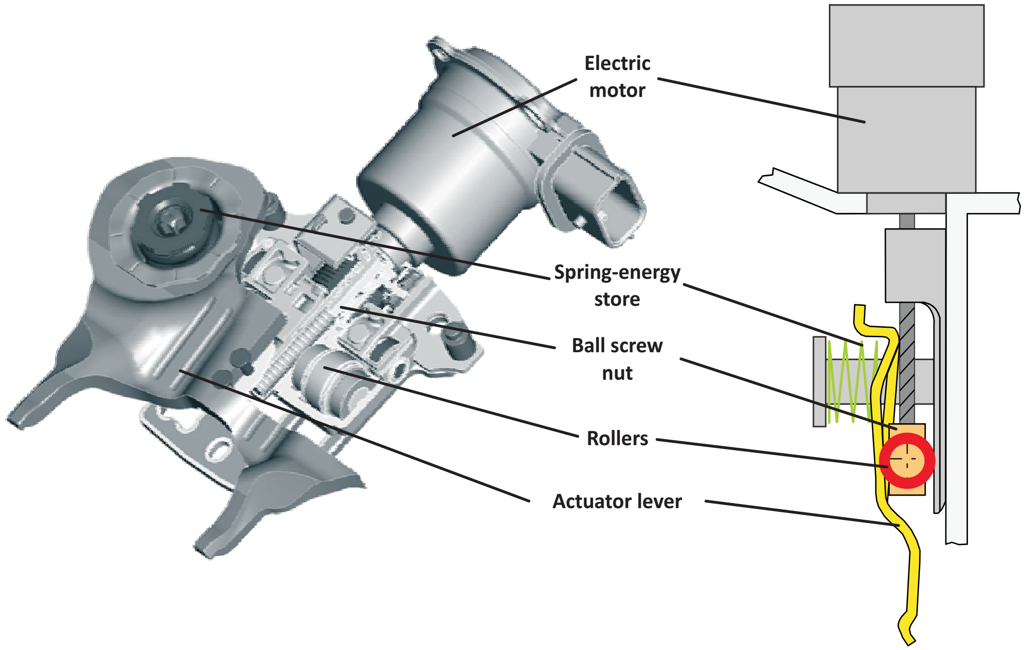

Figure 6 Electromechanical lever actuator for clutch actuation

The newly developed lever actuator (Figure 6) generates the force required for closing the clutches mechanically by means of a spring-energy store [2]. This force acts on the outer end of the rocker-shaped actuator lever. An electric motor that is screw mounted to the transmission housing operates a ball screw drive that moves the support rollers. The support rollers are located between the lever and the transmission housing and support the lever at the center. The lever supporting point and the effective lever ratio can therefore change via the electric motor. The special lever geometry enables a variable transmission ratio between electric motor and clutch so that the electric motor can operate with a constantly low force. Significant reduction of the required motor size is therefore possible for the clutch actuator.

Since the existing elements for transferring the rotary motion of the motor to the linear motion of the actuator did not sufficiently meet the requirements in terms of power density and efficiency, a new ball screw drive has been developed in cooperation with INA. The ball screw drive has four rows with an internal ball return system due to reasons of space. Another unique feature is the specially developed support rollers, which must run very smoothly under loads of up to 7000 N [2], [7].

The double clutch system for the Getrag 6DCT250 transmission has a modular design allowing use of engines with torques between 150 and 280 Nm and combined with different damping systems depending on the vibration excitation. In the standard system, the double clutch has a support bearing on the hollow shaft that retains it axially and radially. Damping of vibrations is by means of an external arc spring damper with a floating flange and preloaded, clearance-free spline teeth. This design is suitable for diesel and gasoline engines with high vibration excitation.

Another variation of the system, designed for engines with low excitation, is a solution with a rigid flywheel and two clutch disk dampers in conjunction with partial micro-slippage control. Here, the double clutch is screw mounted to the rigid flywheel with axial elasticity and radially supported connection (Figure 7). However, a radially floating support bearing on the hollow shaft of the transmission accommodates the axial forces resulting from the clutch actuation. A

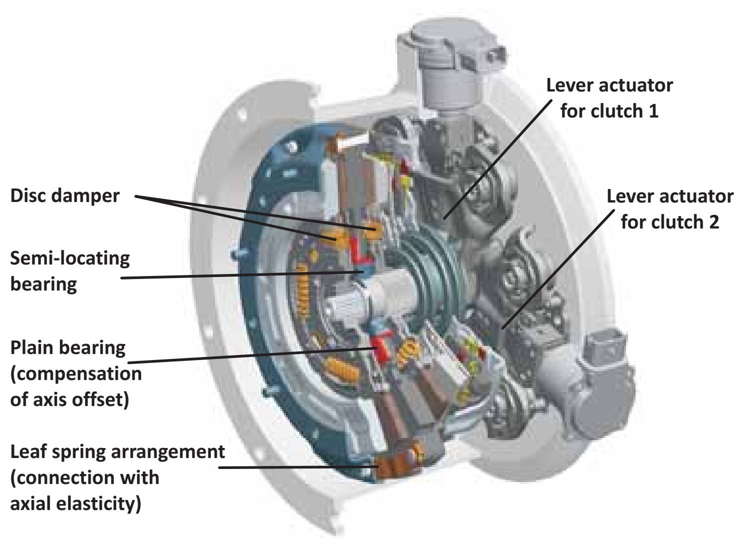

Figure 7 Double clutch system with clutch disk dampers, Getrag 6DCT250

specially developed dry-running axial plain bearing enables radial movement of the semi-locating bearing support towards the double clutch. This is necessary for preventing excessive stresses due to the axis offset between engine and transmission.

The main components of the wear adjustment system with travel sensors in the Getrag 6DCT250 double clutch are a clutch cover with adjustment and sensor ring ramps, as well as one adjustment ramp ring, one sensor ramp ring, clamping springs and adjustment springs for each subclutch (Figure 8). The clutch adjusts when lining wear occurs and the lever spring is forced further in the direction of the engine to generate a specific clamping force. The additional travel of the lever spring lifts the clamping spring, which holds the sensor ring in position. This causes the spring-preloaded sensor ring to rotate by an increment or as far as the clamping spring allows. When the clutch is again completely open due to a gearshift operation, the lever spring is moved to a new position by the rotation of the sensor ring. This also enables rotation of the spring-preloaded adjustment ring by another increment and completion of the adjustment process. Since this travel adjustment system rotates the adjustment ring when the clutch is open, nearly every mounting tolerance can be compensated by rotating the adjustment rings of both clutches. This is particularly advantageous in simplifying mounting the double clutch in the transmission.

When a DCT has an electromechanical clutch actuation system, it is becomes practical to also use

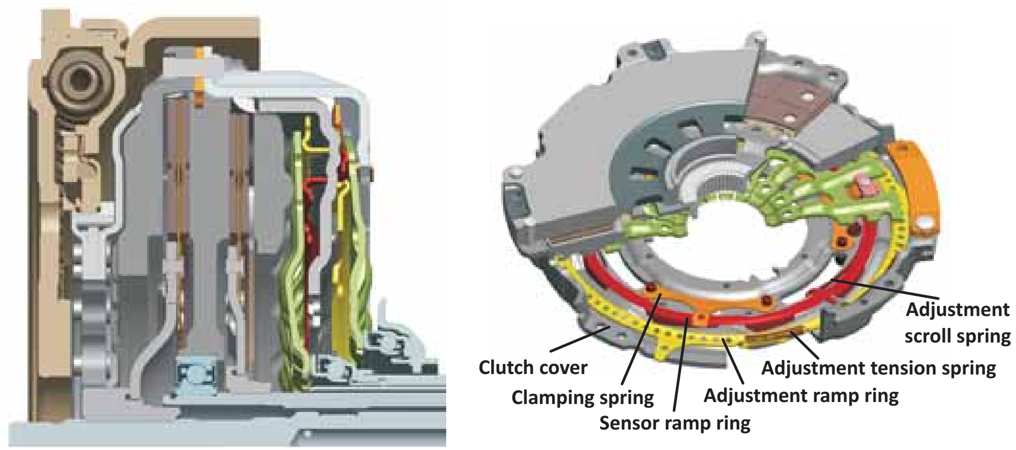

Figure 8 Wear adjustment with travel sensors for double clutches

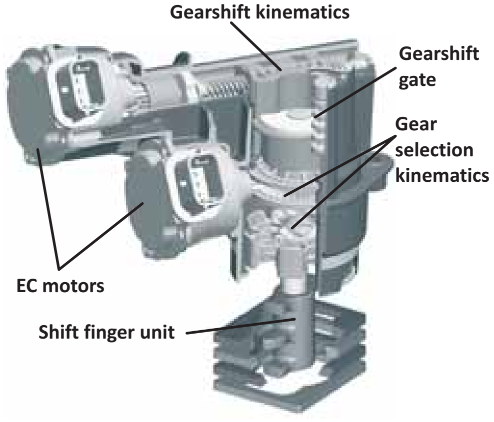

Figure 9 Electromechanical transmission actuator with Active Interlock

an electromechanical transmission actuation system.

An example of such a transmission actuation system is the LuK Active Interlock actuator (Figure 9) [8]. The shift fingers are specially designed so that the gears of both sub-transmissions can be pre-selected and engaged in any combination. The shift finger unit, with interlock and disengagement elements, interfaces with the internal selection system of the transmission. The gears engage by means of the shift finger in a similar manner to the actuation of manual transmissions. The sophisticated Active Interlock system ensures by means of the interlock and disengagement elements that all gears of the same sub-transmission are disengaged before another gear engagement. Elimination of additional sensors for gear detection and the associated monitoring and emergency running strategies are possible due to this simple mechanism. This and the cost-effective design of the mechanical system make the transmission actuator a high-performance product. In combination with the above described lever actuator, it completes the electromechanical clutch and gear actuation system of a DCT.

Control and system characteristics of dry DCT

The dry double clutch system is of great interest to the automotive manufacturers because of its main advantages, namely very high efficiency and excellent driving characteristics. However,

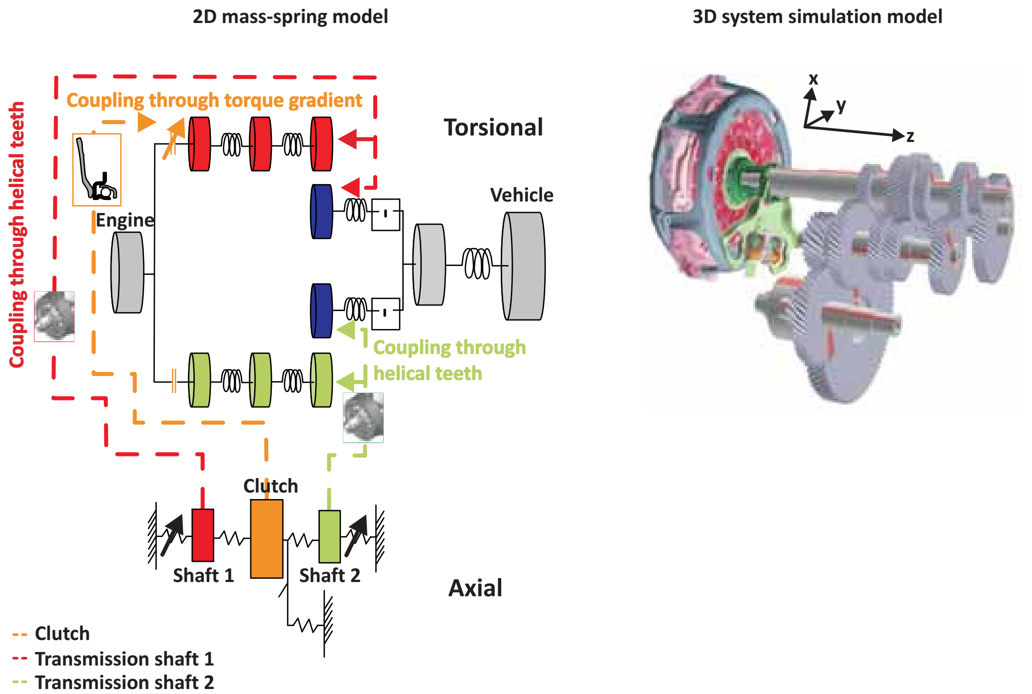

Figure 10 Simulation models for DCTs (coupling of axial and torsional vibration modes)

there are also other advantages worth mentioning. For example, a dry double clutch system with electromechanical actuation is maintenance-free and very robust with regard to contamination and environmental influences. In addition, mounting of the dry double clutch is easy at the transmission and engine plant. Advanced system components such as wear adjustment systems, actuation systems with suitable clutch release and engagement bearings, and damping technologies are also available for many applications.

Production development must include the complex interactions between all drive train components. Newly developed 2D and 3D system simulation tools meet this requirement. Examples of particular interest are calculation models for describing every possible coupling mechanism in the overall system and calculating every conceivable operating condition in advance by means of simulations. Figure 10 shows an example of this.

Production development projects for DCTs reveal that optimizing the vibration and noise behavior is an important prerequisite for success. This involves not only classic torsional damping systems but also vibration modes that feed back due to complex interactions between the two clutches and the transmission structure. Making adjustments are possible using a wide range of system parameters.

For example, the helical teeth of the transmission gears generates an axial motion on the transmission input shafts that and the result in "actuation" of the clutch. This actuation in turn creates a modulation of the clutch torque. This creates a resonance between axial motion and torsional vibration that can cause additional noise. Mapping the system structure in a suitable simulation model for this vibration phenomenon allows adjustments to the system parameters to create stability in the system. A stable system has high system damping, which generates no additional noise. Figure 11 shows the results of a parameter study for this vibration phenomenon.

Optimum function of the DCT depends not only on the hardware components but also on suitable control software that takes the special characteristics of a dry system into account.

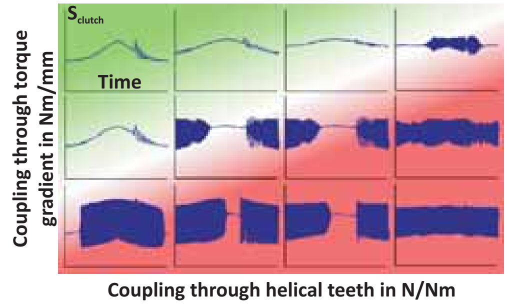

Figure 11 Parameter study for the system behavior of DCTs

The main components of such software are

- the clutch control system,
- the transmission control system,
- the coordination module (which controls the interactions between the clutch and the transmission), and
- the gear selection system (definition of the gearshift points).

Combining these basic components in the software with a diagnostic module for detecting defects in the system and a safety concept for preventing safety-critical situations in the software is required. The requirement for the safety concept derives from the functional and technical safety concept based on a hazard and risk analysis. An example is the stress detection system for preventing undesired stresses on the transmission.

An important prerequisite for implementing optimum control, is detailed knowledge about the clutch and actuator characteristics, their changes depending on the operating conditions and the operating life, and their limits is software. For example, important characteristic curve parameters such as contact point, friction value and hysteresis are permanently adapted online in current volume production projects. Configuring the software to account for other known influencing factors such as temperature, power and speed as well as interactions between the two clutches is required. However, to achieve optimum overall efficiency and driving comfort, the control software must function properly in conjunction with the engine control software.

Summary and outlook

After successful volume production startups for various compact class vehicles, the dry DCT establishes itself in the market as a competent automatic transmission. It has also made a significant contribution to reducing CO_2 emissions due to its excellent system efficiency. Developments of different dry double clutch designs are required due to space constraints and the decision for a special actuator concept for controlling the clutch and the transmission. This shows that modern clutch technologies enable engineers to find a suitable solution for nearly every possible application for a torque range from 150 to 350 Nm. Paying particular attention to the description and simulation of the system behavior from the beginning of the development of a double clutch system is required to achieve optimum efficiency, comfort and durability.

Two trends in the further development of the system will be likely in the next few years. The first is that small vehicles with torques between 120 and 180 Nm will require a compact dry double clutch system. Secondly, these dry double clutch systems will have to operate with even higher torques in design envelopes similar to those of current systems. With its comprehensive system expertise, LuK is able to offer solutions for the increasing requirements for comfort and implement the dry double clutch in a growing number of applications in mid-size vehicles. The dry DCT with electromechanical actuation is an ideal basis for expanding the drive train to include hybrid functions such as stop/start, electric driving and regeneration in conjunction with additional electric motors and appropriate batteries.

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