CVT

High value and high performance

Andreas Englisch
Introduction

The number of continuously variable transmissions produced worldwide is increasing, especially in Asia (Figure 1). In 2015, the total volume – including hybrid drives – will exceed the volume of double clutch transmissions in the market, even when hybrid transmissions with differential drives are subtracted. The increase is the result of the objective of OEMs in Asia and especially in Japan to achieve an optimum drive train in terms of comfort, driving pleasure and efficiency on the basis of a continuously variable transmission. The question is how the expectations of the customers can be comprehensively achieved in future.

The fundamental requirements are identical for all automatic transmissions. The objectives must be higher efficiency, reduced costs, a smaller design envelope and lower weight. As part of the discussion on CO₂, the drive train must also be more compact and lighter. As before, quality and reliability form the basis for success in the market. The new CVT volume applications demonstrate how the aforementioned requirements have been implemented (Figures 2 and 3).

The focus until now has been not only on improved efficiency but also on increased torque capacity. In conjunction with gasoline and diesel engines, it is already possible using LuK CVT technology to achieve up to 400 Nm at power levels of up to 220 kW. When these values are set against the competition, it can be easily seen what progress has been achieved in development. Figure 4 shows the product of torque and ratio spread as a function of the power related to the centre distance. In conjunction with the most powerful application, the Subaru Lineartronic™, it can be seen where the benchmark currently stands.

Figure 1 Volume of CVTs worldwide [2]

What should the CVT of the future look like? One possible answer is a modular transmission concept that allows the specific requirements of customers to be implemented in growing markets.

The Japanese market demands a technical solution that comprehensively addresses the key issues of comfort and efficiency. A transmission without a torque converter is difficult to imagine in this case. In Japan, electro hydraulic clamping and control systems have been under development for several decades and have proved themselves in the market and with end customers. These systems are predominantly combined with single piston systems to achieve clamping. Further advantages can be achieved, however, by expanding this method to include appropriate clamping strategies [5]. The use of the LuK CVT chain also gives a range of advantages for power density and efficiency. On the other hand, there is a certain disadvantage in acoustic terms. Experience has shown that this can be compensated by the use of efficient and easily comprehensible insulation measures in the vehicle in order to fulfill the expectations of end customers, especially in the case of small vehicles.

The markets in China and India are currently oriented primarily towards price and reliability of transmissions. In these locations, however, increasing importance will be attached in future to efficiency and fuel consumption. Especially for these markets, the following “High Value CVT” concept has been developed. Due to platform strategies, it is necessary to introduce different vehicle concepts within one vehicle platform in all markets. The transmission concept must therefore allow easy adjustment of the transmission ratio as a function of the permissible vehicle weight.

Development priorities

The focus of the High Value CVT project was particularly on efficiency (as shown by the colored areas in Figure 5) and the costs of the system. Within the framework of numerous individual tests, it has been possible to quantify the essential efficiency parameters and thereby to set priorities for development. In addition to a new clamping system, geometrical influences were taken into consideration and implemented in the new design of the transmission. The individual stages of development are discussed in detail in the following sections.
mission should fulfill the potential customers expectations as envisaged.

**High Value CVT**

The concept

The transmission concept must in principle allow the use of various starting elements. Depending on the market and input torque, this may be a dry or wet starting clutch. In the comfort-oriented markets, the torque converter will continue to be the first choice. The High Value CVT envisages the use of a wet clutch as a starting element. The particular advantage lies in the strategic capability of the starting element. The input clutch can in principle be operated by electromechanical or hydraulic means. Appropriate actuators are already envisaged within the development framework of the automated manual transmission and for double clutch transmissions.

The torque sensor has proven itself in many applications. In conjunction with small, supercharged engines, it ensures optimum setting of the clamping pressure. For the High Value CVT, a new type of five-stage torque sensor was developed which will be discussed in more detail later. In the stated markets, it should also be assumed that drivers must also travel on poor roads. It is therefore all the more important to avoid conditions with damaging slip between the chain and the pulley surface. This has been taken into consideration in the design of the hydraulic system.

The pulley set has a double piston on the primary pulley set and a single piston on the secondary pulley set. Due to the improved piston surface design, the maximum pressures and the package can be minimized and the pump size optimized at the same time. Furthermore, the design ensures that the clamping pressure remains the determining pressure in the system over wide ranges. This gives a further fuel consumption advantage when using the torque sensor in the pressure system.

In conjunction with the newly developed 07th chain type, the centre distance of 155 mm allows an overall Ratio of 7.7. This large overall ratio ensures that the engine operates close to its optimum and thus allows low consumption.

As part of these considerations, a pulley set made from sheet metal components was developed, allowing significant reductions in costs and weight. The fixed and movable sheaves are made from sheet metal components joined by friction welding and are in some cases connected to cold formed shafts by means of press fits. This design of pulley sets reduces the weight of the pulley sets while retaining high rigidity. In order to achieve a further reduction in costs, a mechanical reverse gear with synchronization and an inverted tooth chain drive is planned. On the output side, the new lightweight spur gear differential from Schaeffler is used for package and weight reasons.

**Cost efficient pulley set**

Simple concepts with a single piston and electronically controlled clamping pressure can also be opti-
mized in terms of cost by means of pulley sets made from sheet metal. The most cost-effective variants involve the use of identical parts and a design of the pulley sets based on parts of almost the same dimensions (Figure 8). In addition to formed sheet metal parts, kneaded shafts are used.

The optimum design of adjustment and clamping areas

Before design work is started, a decision must be made which concept has to be implemented in relation to the adjustment and clamping areas. Two concepts were included in the narrower selection. The double piston principle used in previous volume applications envisages a separate pressure chamber on each of the primary and the secondary pulley set for clamping and adjustment of the variator [10]. Pressure can be applied to both chambers independently.

When the second concept is being checked, the question is whether an advantage can be achieved in relation to consumption through the omission of the adjustment chamber on the second pulley set. In this case, an adjustment pressure can be overlaid on the clamping pressure in the same chamber by an additional increase in pressure, the adjustment pressure being necessary to support the equilibrium or to change the ratio of the variator. The pressure is set by means of the differential pressure valve VSS2 described in the section “Hydraulic system”.

Both concepts use the proven hydraulic connection between the two clamping pressure chambers already implemented in volume applications. This has a positive effect on the hydraulic volume flow balance in adjustments and thus offers the advantage that a smaller design of hydraulic pump can be used. This reduces both the power consumption of the pump and the associated losses.

In order to assess the two concepts, several different driving situations were analyzed with rapid adjustment of the variator that were used to determine the size of the hydraulic pump. In addition, the consumption cycles NEDC and JCOB valid for Europe and Japan were used in order to minimize the losses of the variator and the torque losses of the predefined hydraulic pump and thus achieve one design which is optimized with regard to fuel consumption for different markets.

The analysis shows that, under the boundary conditions present here, there is an advantage to the concept that overlays the clamping and adjustment pressure on the secondary pulley set in one chamber. The advantage of the single piston principle compared to the concept with two separate pistons for pressure and adjustment is approximately 10%. This statement relates to the losses of the variator and the hydraulic pump. Figure 9 shows in detail the pressure chamber (red), the adjustment chamber (green) and the five-stage torque sensor (blue) of the primary pulley set. In addition, the single piston (red) and the pressure chamber for centrifugal oil compensation (blue) on the secondary pulley set are shown.

An investigation of various area designs is performed by varying the radius $R_1$ of the primary pulley set and the radius $R_2$ of the secondary pulley set independently of each other. Through variation of $R_2$ and thus the clamping area $A_2$, it is also possible to change the area of the adjustment chambers, although not independently of each other. For each pair of values of the areas $A_1$ and $A_2$, the necessary size of the hydraulic pump is first determined and this value is then used in a second stage to calculate the energy loss of the variator and the energy consumption of the hydraulic pump for different consumption cycles.

Figure 10 shows the result of a variant calculation based on the NEDC. A similar representation is given for the Japanese JCOB. The area design with the minimum losses from the hydraulic pump and variator that simultaneously fulfills other design boundary conditions and was implemented in the draft in Figure 7 has been highlighted. In addition, it should be pointed out that this tool can be used very easily to optimize the switchover points that are realized with the five-stage torque sensor in relation to the different consumption cycles.

The clamping system

The simplest system envisages, as previously mentioned, the use of identical pulley sets on the primary and secondary pulley set in combination with an electronic clamping system. This system allows slippage-controlled adaption [5] of the clamping pressure. Since there are now almost 1.5 million Audi multitronic® transmissions in the market, the advantages of the torque sensor for adjusting the clamping pressure have been successfully demonstrated on a broad basis. The essential advantage lies in the reliable recording of the drive torque – especially in the low-load range significant for consumption – and the precise and dynamic adaptation of the adjustment of the clamping pressure to the specific situation.

The torque sensor represents, in conjunction with small supercharged engines, the resulting less precise torque signals and the partially poor roads in the emerging markets, a significant component in increasing reliability. The further increase required in torque capacity has required the development of the fully variable torque sensor (vTS). The sensor adapts the clamping pressure in an optimum manner to the clamping requirement of the variator. However, this is a technically complex variant and accordingly does not represent the most cost-effective solution. As part of the multitronic® development, possibilities were sought for achieving a more cost-effective variable torque sensor.
The orifice torque sensor

The orifice torque sensor (OTS) is based on the economical, two-stage torque sensor (2TS). Its five-stage design makes it possible to significantly reduce excessive clamping pressure. For example, the clamping pressure in the ratio range $0.4 < i_{\text{var}} < 0.68$ that is significant for consumption was reduced by 8% compared to the 2TS. In addition, the maximum load on the pulley set shafts in particular is significantly reduced, which allows smaller cross-sections to be used with corresponding advantages in terms of weight and ratio spread.

The costs are at approximately the same level as those of the established two-stage torque sensor. It is realized by using orifices B1 to B4 in the primary pulley shaft. Depending on the position of the movable pulley, a different number of orifices are released and the clamping pressure is set accordingly. The function of the OTS is confirmed by comprehensive tests on a test rig and in the vehicle. For front end transverse applications, the design can also be configured so that the torque sensor does not determine the overall length. In this case, the balls and ramps are arranged within the multi-disk clutch in order to give a shorted pulley set and achieve the required overall length.

The new chain portfolio

LuK uses traditional chains for CVT. In addition to the functional advantages of the chain, there is a significant benefit from their modularity. Due to their construction of link plates and rocker pins, the LuK CVT chain was driven forward and a very high performance capacity was identified. The aim here is to combine the advantage of the chain (efficiency, robustness, large overall ratio and improved acoustics spread, etc.) with the further potential of a smaller geometry.

Irrespective of size, LuK CVT chains have also undergone further development of the design. One development item, for example, is the optimization of the contact conditions between the chain and the guide rail. The function of the guide rail is to suppress strand oscillation effects and is in contact with the outside profile of the links during operation. The outside profile of previous chains had cams in order to give secure location of the links during assembly. In the course of further development, these were replaced by dents in order to prevent possible pitting effects on the guide rail (Figure 14). This optimization is of course neutral in terms of strength and can be applied to all the types and sizes of chains under consideration here.

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Chain type 07

The chain type 07 represents, in simplified terms, a scaling down of the type 08 with additional detailed optimizations. The use of type 07 gives primarily geometrical advantages that are reflected, for example, in a reduced design envelope or a significant increase in overall ratio (Figure 15). In order to make use of these advantages, the small chain must fulfill the necessary strength requirements. Tests carried out show that the chain type 07 allows transmission of high torques and has the potential to replace chain applications with large pitch across wide areas.

Chain type 06

As described in the preceding section, a reduction in the size of the chain type (transition from 08 to 07) brings a series of possible advantages. One interesting question is now to what extent it is advisable to reduce the size of the chain further. In order to answer this question, an even smaller version of chain type 06 was designed and assessed using simulations. As the individual parts become smaller, their strength decreases first. On the other hand, this leads to effects that can have a positive influence on the loading of the chain. Where a smaller chain pitch is present, for example, the frictional force between the chain and pulley set is split between a larger number of joints. This leads to more uniform load distribution.

Once all these conditions are taken into consideration, the chain type reduced in size by 10% (transition from 07 to 06) can be expected to show the performance capacity shown in Figure 14. In terms of chain width, it achieves approximately the performance capacity of chain type 07. As a result, this chain is virtually the obvious choice for passenger car applications with low or moderate torque values or even for applications in the two-wheeler sector.

A decisive motivation in reducing the size of the chain is the possibility of influencing acoustic characteristics. The chain 06 offers not only a reduced weight but also a significantly lower chain pitch, which gives a reduction in the excitation level due to polygonal running. Furthermore, the smaller pitch changes the excitation frequencies. The acoustic effects of this new chain must be assessed in an actual environment and a further improvement in the acoustic behavior compared to previous chains can be assumed.

Output stage/reverse gear

On the output side, a spur gear transmission is envisaged that allows a maximum ratio between 14 and 19. With this design range, it should be possible to achieve the necessary starting traction force or hill climbing ability for all vehicles based on one platform. The output stage allows the integration of the reverse gear in conjunction with a synchronization unit, dog clutch or multi-disk clutch.

Lightweight differential

The lightweight differential is designed as a spur gear differential. Significant components such as the planet carrier are designed as sheet metal parts in order to allow economical, optimized weight solutions. As a further advantage, this arrangement allows the use of sufficiently long driveshafts.

Hydraulic system

The hydraulic system supplies the functions of clamping, adjustment, clutch actuation, clutch cooling and cooling of the pulley sets. The oil conveyed by the pump flows via a pressure control valve (VVS1) and a differential pressure valve (VSS2) to the torque sensor, which operates in the established manner as pressure control valve. After the torque sensor, this oil is used directly for cooling of the clutch. The system offers the possibility of varying this volume flow by directing portions of the oil conveyed by the pump in parallel via the volume control valve and a minimum pressure valve (VMD) back to the suction tract of the pump. Ahead of the VMD, the oil is branched off for cooling of the pulley sets and for lubrication.

The variability of the volume flow to the torque sensor ensures a minimum supply on the one hand and also achieves the minimum requirement for cooling of the clutch. On the other hand, it is also possible to provide a high volume flow for maximum clutch cooling. The system pressure is determined primarily by the torque sensor. Where a higher system pressure is required for adjustment, an increase can be managed by VVS1 or VSS2. The pressure reduction valves VKSI, VKA and VSS1 are connected to the system directly after the pump and draw off the pressure oil that they require to supply the functions controlled by them. The VSS1 adjusts the pressure in the adjustment chamber 1 and thus provides the support of clamping force ratio or the change of variator ratio, which itself requires an additional axial force on primary pulley set. The pressure is also used as a control pressure for VVS1 in order to increase the system pressure as required. The VKA adjusts the clutch pressure. If a defect occurs, the VSI can reduce the clutch pressure en route to the clutch. The VKS1 sets a pressure for control of the VK. The VKK varies the control value for the VQP and thus achieves the aforementioned control of the volume flow. The VKS1 pressure is also used for switching of the VSI. The clamping pressure in the single piston of secondary pulley set is also specified by the torque sensor. In order to achieve a certain clamping force ratio or adjustment, in which an additional axial force on the secondary pulley set is required, this pressure

<table>
<thead>
<tr>
<th>Chain type</th>
<th>Minimum running radius</th>
<th>Chain mass (for same length and width)</th>
<th>Chain height</th>
<th>Chain pitch</th>
<th>Acoustics</th>
<th>Life</th>
<th>Efficiency</th>
<th>Production technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLD08</td>
<td>30 mm</td>
<td>-10% compared to CLD08</td>
<td>12.2 mm</td>
<td>8.5 mm</td>
<td>Significant advantage for CLD07 (up to 3 dB improvement in near field)</td>
<td>Approximately comparable (based on tests)</td>
<td>Approximately comparable (based on tests)</td>
<td>To be assessed</td>
</tr>
<tr>
<td>CLD07</td>
<td>27 mm (-10%)</td>
<td>(-10% compared to CLD08)</td>
<td>11.2 mm</td>
<td>7.6mm</td>
<td></td>
<td></td>
<td></td>
<td>To be assessed</td>
</tr>
<tr>
<td>CLD06</td>
<td>24.3 mm (increase in spread by approx. 20%)</td>
<td>-10% compared to CLD07 (for same length and width)</td>
<td>10.1 mm</td>
<td>6.9 mm</td>
<td></td>
<td></td>
<td></td>
<td>To be assessed</td>
</tr>
<tr>
<td></td>
<td>(for same length and width)</td>
<td></td>
<td></td>
<td>(-10% compared to CLD07)</td>
<td></td>
<td></td>
<td></td>
<td>To be assessed</td>
</tr>
</tbody>
</table>

Figure 15 Comparison of chain types
must be increased above the torque sensor pressure. The differential pressure valve VSS2 is arranged between the single piston on secondary pulley set and the clamping pressure chamber on primary pulley set or the torque sensor. It is thus able to set a higher pressure in secondary pulley set than that specified by the torque sensor.

Assessment of the High Value CVT on the NEDC

The efficiency optimizations described in previous sections for the High Value CVT were assessed in relation to consumption on the NEDC. The boundary conditions selected for simulation included the following vehicle and drive train parameters:

- vehicle weight: 1200 kg (A platform)
- engine specification: 73 kW / 150 Nm petrol
- High Value CVT: overall ratio 7.7 / starting ratio 14.5 / overdrive ratio 1.9

For comparison purposes, a drive train with a 5 speed manual transmission (MT) was selected that corresponds to the current level of technology in this weight and power category. The starting ratio used in the MT is 15.6, while the overall ratio in the highest gear is 3.7. This gives an overall ratio of nearly 4.3. In addition, the drive train was investigated with a manual transmission of the following variants, in order to cover the latest trends:

- 5 speed MT with gearshift recommendation
- 5 speed MT with gearshift recommendation and differential ratio 10 % higher

The latter variant is suitable for presenting a comparison with a manual transmission for optimized consumption. With an overall spread of 4.3 it is not possible, however, to increase the axle ratio by more than 10 % without having to accept disadvantages in terms of starting dynamics, acceleration and hill climb ability. In contrast, the High Value CVT with an overall ratio of 7.7 achieves not only good acceleration values but also reduced fuel consumption due to an overall ratio in overdrive of less than 2. This advantage is reflected in the simulated NEDC consumption, which is shown for different variants in Figure 17.

Conclusion

CVT is an established part of the automotive world, with the current focus undoubtedly in the Asiatic region. Starting from these markets and sustained by new, interesting applications, a further increase in market share can be anticipated for the future. CVT cannot elude current demands for a further increase in efficiency. In order to achieve success here, however, it is necessary to consider the complete system in a comprehensive manner. This shows that even current CVTs – especially in conjunction with clamping pressure systems based on the torque sensor – still have further potential for optimization in terms of efficiency. In comparison with manual transmissions, savings of more than 5 % are a realistic prospect.

For the drive trains of the future, components that give higher power density within an improved package will be ever more important. It will be necessary to take account of apparently contradictory aspects such as price sensitivity and reliability. Based on the example of the High Value CVT, it has been shown how these requirements can be fulfilled through rational further development of the components.

Literature