1 Abstract

Efficiency, package and weight are becoming more and more important in automotive industry. At the same time, drivers do not want to do without driving comfort and driving fun. Continuously variable transmissions (CVT) represent an excellent way to meet these requirements, which is evidenced by the data from current CVT applications.

The number of CVTs produced worldwide has been increasing, above all in Asia-Pacific. New production applications have confirmed this trend.

Despite the already very good current designs, experts are continuously working on improving the details of CVTs. The effects of these improvements (e.g. efficiency) can be described very clearly using measurement results and simulation results.

CVTs can be used effectively in applications ranging from small cars to luxury vehicles. However, this requires the relevant components to be adjusted to a specific application. In this paper, the CVT chain is used to show how this element can be scaled in the lower torque range, for instance, to meet requirements for package, mass, power density and ratio spread.

2 Introduction

Like never before in the history of the automobile, a wide range of automatic transmission designs are currently competing with one another.

In addition to the more and more improved classic stepped automatic transmissions with torque converters, which are typically offered with 6, 7 or 8 gears, the European market in particular features many new dual-clutch transmissions.

CVTs have begun to primarily conquer the Asia-Pacific market, starting with Japanese OEMs. In Europe and North America, it has gone largely unnoticed that the CVT share in Japan has increased to 45% of all new passenger cars. For four-cylinder engines, this share is even higher at 63% [1]. Global CVT production is currently at roughly 4 million units annually. The introduction of new CVTs not only in Japan but also in the NAFTA and EU regions as well as the activities of various Chinese manufacturers are expected to increase global CVT production further.
The latest generation of CVTs is unparalleled when it comes to comfort, and it also has the potential to become a benchmark for fuel consumption. Due to its principle, the efficiency of a CVT may not be better than that of, say, a dual-clutch transmission, but this perceived disadvantage may be overcompensated by the continuously variable design and the selection of the optimal operating point in the engine map. This can result in better fuel consumption than what could be achieved using manual transmissions (MT) [2], [3].

3 CVT Applications with LuK's Technology

3.1 AUDI multitronic®

Ever since the very beginning of AUDI's CVT development, LuK has been responsible for developing and producing the CVT key components for multitronic®: Pulleys including a special clamping and ratio adjustment system, chain, guide rail and hydraulic control unit.

![Figure 1: AUDI's longitudinal FF-CVT multitronic®, 2nd generation](image)

When production started in 1999, AUDI's multitronic® was solely applied to V6 - 2.8L (142kW/ 193hp, 280Nm) gasoline engines in AUDI's A6. This was the first high torque/ high power application for engines above 2.5L and for the European market, with heavy road loads (e.g. no top-speed limitation) and high average mileage per year.
Replacing a 5-speed AT, the non-MT share almost doubled due to the CVT's excellent fuel consumption (less than 5AT and MT), performance (better 0 - 100 km/h acceleration than 5AT and MT) and no top-speed limitation (231 km/h).

From 1999 - 2009, AUDI introduced the multitronic® - now available as the 2nd generation - for numerous gasoline and diesel applications. Today the range is as follows [2]:

**Gasoline engines:**
- Min. I4 - 1.8TFSI 118kW/160hp, 250Nm, Turbo
- Max. V6 - 3.2FSI 195kW/265hp, 330Nm, naturally aspirated

**Diesel engines:**
- Min. I4 - 2.0TDI 105kW/143hp, 320Nm, Turbo
- Max. V6 - 2.7TDI 140kW/190hp, 400Nm, Turbo

The multitronic® covers three platforms (A4/A5, A6, A8) with plenty of body styles (Notchback sedan, Wagon, Coupé, Convertible).

Overall production volume has reached more than 1.3 million units. Currently production runs at approx. 1,000 sets/day. Sold worldwide, China’s demand in particular has been growing rapidly, with a current share of nearly 50%.

### 3.2 Fuji Heavy Industries/ SUBARU Lineartronic™

In April 2009, another CVT using technology made by LuK was introduced: Fuji Heavy Industries Ltd. unveiled its MY2010 SUBARU Legacy as well as the MY2010 SUBARU Outback at the New York International Auto Show.

![Figure 2: FHI/ SUBARU’s longitudinal AWD-CVT Lineartronic™](image)

The drive train combines SUBARU’s horizontal-opposite (HO) engines with Lineartronic™, a brand-new longitudinal, highly efficient AWD CVT with torque converter as a start-up device (fig. 2). LuK supplies chains and guide rails to FHI and supported the pulley system development.
The first application of Lineartronic™ comes with HO4 - 2.5L naturally aspirated engines, delivering 125kW/ 170hp and a maximum torque of 230Nm. However, the pulley and chain system have already been successfully developed and tested up to 220kW/ 300hp and a maximum torque of 400Nm. This offers a wide range of possible engine applications. Taking the pulley system’s small center distance (169.5mm) and wide ratio coverage (6.32) into account, a new benchmark in terms of power density and compactness was achieved (fig. 3).

![Figure 3: Benchmark of LuK Chain vs. push-belt CVTs](image)

4 Measures to Increase Efficiency
Efficiency and CO₂ emissions have become the dominating topics in the continued development of drive trains. The fact that CVTs have been used in passenger cars for many years might lead to the impression that the efficiency potential for CVT components has been largely exhausted. However, in view of the number of parameters that impact the efficiency of a CVT, additional and significant improvements are certainly possible. Losses of CVT-specific components roughly can be classified as follows:

- Contact loss between chain / push belt and pulley sets
- Internal losses of chains / push belts
- Pump losses and
- Bearing and drag losses

In addition, the ratio spread, the driving strategy and the weight of the components all have an effect on the CO₂ emission. Each of the sources of loss indicated is in turn influenced by a large number of parameters.
LuK’s CVT development group has started a new analyzing program focusing on the parameters that affect a large number of loss sources. This includes:

- the rigidity of the variator components
- the contact and crowning geometry of the chain and pulley sets and
- the accuracy of the clamping force

4.1 Optimization of Frictional Contact between Pulley Sets and Chain

Due to the complexity of this topic, calculations and simulations are required prior to testing. LuK has developed a simulation tool that clearly shows the sources of loss for the variator. Simulations show, for instance, that the exact position of contact points between the rocker pins and the pulleys plays a decisive role, besides the rigidity of the pulley sets.

The calculation example (fig. 4) shows how optimizing the tip end geometry of the rocker pins can save a power loss of approx. 70W for a part load operating point in the overdrive range. The greatest loss reduction can thus be achieved for the fixed sheave (FS) and movable sheave (MS) on the driven pulley set. Test results have confirmed this calculation and shown that optimization has a positive effect on the entire transmission range (fig. 5). The contact loss reduction also has a positive effect – as was to be expected – on contact wear and the required amount of cooling oil.

![Figure 4: Simulation contact losses (speed ratio=0.5, 100Nm, 1300rpm)](image1)

![Figure 5: Measurement efficiency (100Nm, 1300rpm)](image2)

4.2 Optimization of the Cone Disc Profile

The geometry of the V-pulley is another important parameter. Tests using various cone angles, with and without superimposed crowning radius, have shown overdrive...
improvements of 1 to 3% in the part load range (fig. 6) for transmissions relevant for fuel consumption.

Figure 6: Comparison of standard sheaves to 11° crowned sheaves @ 1300rpm

It has been determined that the best variant here is a geometry with a cone angle of approx. 11° with a superimposed crowning radius. Variants with a crowning radius generally achieve better efficiency than comparable variants with a constant cone angle.

Figure 7: Sheave geometry: Clamping force ratio ($\zeta$) vs. speed ratio
A larger cone angle and superimposed radius also have a positive effect on the clamping force ratio of the variator (fig. 7). In the operating points, where the adjusting pressure is defining the system pressure, the pump power can also be reduced. These tests too have shown that there is a distinct correlation between contact losses and contact wear.

4.3 NEDC Analyses

LuK performs consumption simulations in advance followed by vehicle or test bench measurements to analyze the effects efficiency improvements have on consumption cycles. Among other things, adjustments have been necessary due to the temperature profiles of the engine and the transmission. The chart below shows the ATF and engine temperature profile of an NEDC measurement. The mean engine temperature was only 53°C. The mean ATF temperature of the CVT was even lower at just 35°C. Consequently, efficiency measurements at 80°C or 100°C, which are still common, are of little use. Incidentally, this is not only true for the consumption cycles. Analyses of real customer applications have also shown that the effective engine and transmission temperatures are significantly lower than generally assumed.

![NEDC measurement with CVT](image)

Figure 8: NEDC measurement @ test bench with CVT

Low temperature and load levels lead to additional approaches that may significantly improve efficiency:
• Switching off the cooling cycle for the transmission in the lower temperature range (e.g. via a bypass valve) to accelerate transmission heating
• Use of a hydro-mechanical torque sensor [4] (considerably more accurate than the torque information supplied by the engine control unit)
• Reduction of pressure losses and pressure offsets in the hydraulic system

Switching off the cooling cycle increased the mean ATF temperature in the NEDC by approx. 5K compared to a cooling cycle in continuous operation. Heating the transmission via the engine water is not a good idea, however, since the engine’s fuel consumption map is much more sensitive to temperature than the efficiency of the transmission.

4.4 Effect of the Clamping Force on Efficiency

The test described below shows the sensitivity of the variator efficiency to over clamping, even for part loads.

The clamping force varied in this test. In the example shown (50Nm, 2000rpm), over clamping by just 0.25MPa increases variator losses by approx. 2% in OD and 1% in UD. Over clamping the variator directly or indirectly (via higher adjusting pressures) leads to higher system pressures, which further reduces the efficiency of the transmission. Precise clamping even at low temperatures and low loads is indispensible for achieving greater transmission efficiency.

![Figure 9: Efficiency vs. speed ratio for 50Nm, 2000rpm](image-url)
4.5 Optimization of Hydraulic Control

The mean variator torque in NEDC is only around 60Nm for a mid-size car. In this low-load range, minimum pressures, clamping deviations and pressure offsets in the hydraulic system have a particularly strong effect.

When it comes to clamping accuracy, it is especially in the low-load range that the hydro-mechanical torque sensor used in LuK variators has the greatest benefits compared to an electronically controlled clamping system.

Due to temperature-sensitive minimum pressures, it has not been possible to fully utilize the advantages the torque sensor in the NEDC has to offer. Further optimization has now resulted in a significant reduction of minimum pressures in cold transmissions, which in turn reduces variator clamping by approx. 0.5MPa. This not only improves variator efficiency but also lowers the system pressure by approx. 0.3MPa in the NEDC.

The pressure offset between the adjustment pressure and the system pressure has been reduced, particularly in the part load range relevant for consumption (fig. 10). With the exception of stationary times, this has a direct effect on system pressure (-0.25MPa in the NEDC) in nearly all driving situations.

A stop washer has been integrated in the pump to ensure that the pump can quickly and reliably intake oil, even in the case of a cold start. This plate, however, results in a pressure offset of 0.1MPa. This offset has been eliminated completely (below the minimum system pressure) by changing over the cold-start plate from a differential pressure valve to a minimum pressure valve.

![Figure 10: Pressure offsets between adjusting and line pressure](image-url)
Since the pump’s system pressure is often determined by the adjustment pressure, measures that reduce the adjustment pressure are also helpful. The pressure chambers in LuK’s variators are separated into a clamping cylinder and an adjustment cylinder [5], so that the simplest way is to enlarge the adjustment surface on the primary pulley set. However, this has an effect on the maximum adjustment speed in OD direction. An analysis of the volume flow balance has shown that increasing the adjustment surfaces by 15% is permissible. This allows the adjustment and system pressures to be reduced by an additional 0.1MPa.

Together, all of these hydraulic measures have decreased variator pressure by an average of 0.5MPa and pump pressure even by 0.75MPa in the NEDC.

4.6 Evaluation of CVT Efficiency in NEDC

All of the measures have been combined in an efficiency package. The following optimizations have been implemented:

- Optimized rocker pin profile of the tip end
- Optimized crowning profile on the pulley sets
- Reduced minimum clamping pressure
- Reduced pressure offsets in the control unit and pump
- Increased adjustment surface on primary pulley
- Shift of clamping spring of secondary pulley set to primary pulley set.

![Figure 11: NEDC fuel consumption standard vs. optimized transmission (average of 7 measurements)](image-url)
The package was evaluated on the test bench with regard to efficiency and consumption. Consumption measurements were taken on a 3.2L gasoline engine using a combustion engine test bench, with seven measurements each. The starting temperature for the NEDC was set uniformly at 20°C. At the same time, NEDC simulations were carried out with and without the package of measures described above. Compared to the measurements taken, the simulated results showed a somewhat smaller consumption advantage. This is believed to be due primarily to the fact that only the consumption map of warm engine was available for the simulation. NEDC measurements for various starting temperatures allow the conclusion to be drawn that the engine’s fuel consumption map has an extremely strong dependency on engine temperature. In the NEDC, a fuel consumption benefit of nearly 6% was measured using the package of measures described above.

5 What's Next in Automotive Engineering?
The efficiency measures described above are not limited to a specific vehicle category. An important question, however, is what cars are going to look like in the future. There are a number of possible trends and scenarios (fig. 12). It is highly likely that combustion engines will continue to dominate in automobiles in the future. Different than today’s commonly used drive trains, however, the integration of additional functions such as start/stop capability and hybridization will determine their viability.

![Figure 12: Trends in vehicle manufacturing](image-url)
CVTs were originally used in vehicles with small engines. As a result of technical developments and the advantages of this transmission design, it was later established for use in mid-size and full-size luxury vehicles. One of the factors that made this step possible was the use of chains for CVT variators.

It must be said, though, that the growth of torques and vehicle performance has slowed. This does not necessarily mean that driving fun and driving comfort are going to fall by the wayside. On the contrary, what is important here is to use the installed engine performance as efficiently as possible and to increase the power density of the units.

Fig. 13 uses the CVT chain as an example for demonstrating how LuK is reacting to these requirements. The types of chains shown here cover a torque range of just under 100Nm up to 600Nm. This means that the very high level of efficiency [6] and the power density of the CVT chains can be used for the entire range of passenger car applications.

The applications covered by LuK’s volume production so far have been for mid-size and full-size luxury cars. Due to the flexible design of the CVT chain, which consists of links and rocker pins (fig. 14), simply joining the components in a different way allows nearly the entire torque range to be covered.

Chain type LK07 has been developed with a width of 24mm (fig. 13) for applications up to 200Nm. To put it simply, this design is a smaller variant of chain type LK08 with reduced pitch.

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![Figure 13: Chain components including current development for small chain type](image-url)
Type LK07 offers significant benefits with regard to the required design space and mass (fig. 15). Whether additional benefits can be generated for the transmission as a whole depends on the specific design.

The geometry advantages described above can only be implemented if the performance of the chain is ensured in spite of the miniature design. A smaller design initially weakens individual components, such as the chain link plates. This does not necessarily happen in the chain as a whole, however. As a result of the smaller chain pitch, the frictional force may be distributed across a larger number of joints when it comes in contact with the pulley sets, which results in a homogeneous load distribution.

<table>
<thead>
<tr>
<th></th>
<th>LK08</th>
<th>LK07</th>
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<tbody>
<tr>
<td>Minimum running radius</td>
<td>30mm</td>
<td>27mm (-10%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[theoretical advantage for ratio spread of approx. 20%]</td>
</tr>
<tr>
<td>Chain mass</td>
<td>LK07 has an advantage of 10% (for same width and length)</td>
<td></td>
</tr>
<tr>
<td>Chain height</td>
<td>12.9mm</td>
<td>11.6mm (-10%)</td>
</tr>
<tr>
<td>Basic chain pitch</td>
<td>8.5mm</td>
<td>7.6mm (-10%)</td>
</tr>
<tr>
<td>Acoustics</td>
<td>clear advantage for LK07 (up to 3dB measured in transmission near field)</td>
<td></td>
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<tr>
<td>Durability</td>
<td>largely comparable (based on tests)</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>largely comparable (based on tests)</td>
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<tr>
<td>Production technology</td>
<td>comparable, i. e. based on wide mass production experiences</td>
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Figure 15: Comparison of chain type LK08 and LK07
Testing of chain type LK07 with larger widths is ongoing. Preliminary test results have fully confirmed the expected potential. Type LK07 shows a rigidity similar to type LK08 if a reasonable width is selected. The described properties fully meet the current requirements for reduced design space and mass with high performance levels. Together with increased ratio spread additional acoustic benefits increase the attractiveness of this chain type.

6 Summary

CVT transmissions are an integral part of the automotive world, the current focus being on Asia-Pacific. Starting in these markets, and supported by interesting new applications, the market share for CVTs is expected to increase further. Current requirements for further improving the efficiency of products also apply to CVTs. Making successful improvements requires a comprehensive evaluation of the entire system. Initial results have shown that current CVTs offer sufficient potential for efficiency optimization. Compared to today’s CVTs, which are already very good, additional savings of more than 5% are realistic. For future drive trains, components with high power density for reduced design spaces will become increasingly important. This paper uses the CVT chain as an example to show how consistently continuing the development of components can help meet these requirements.

7 Literature

[1] www.marklines.com
   Auto Industry Analysis Report No. 743, Jan. 23, 2009


   LuK CVT Components for Future Efficient Drivetrains