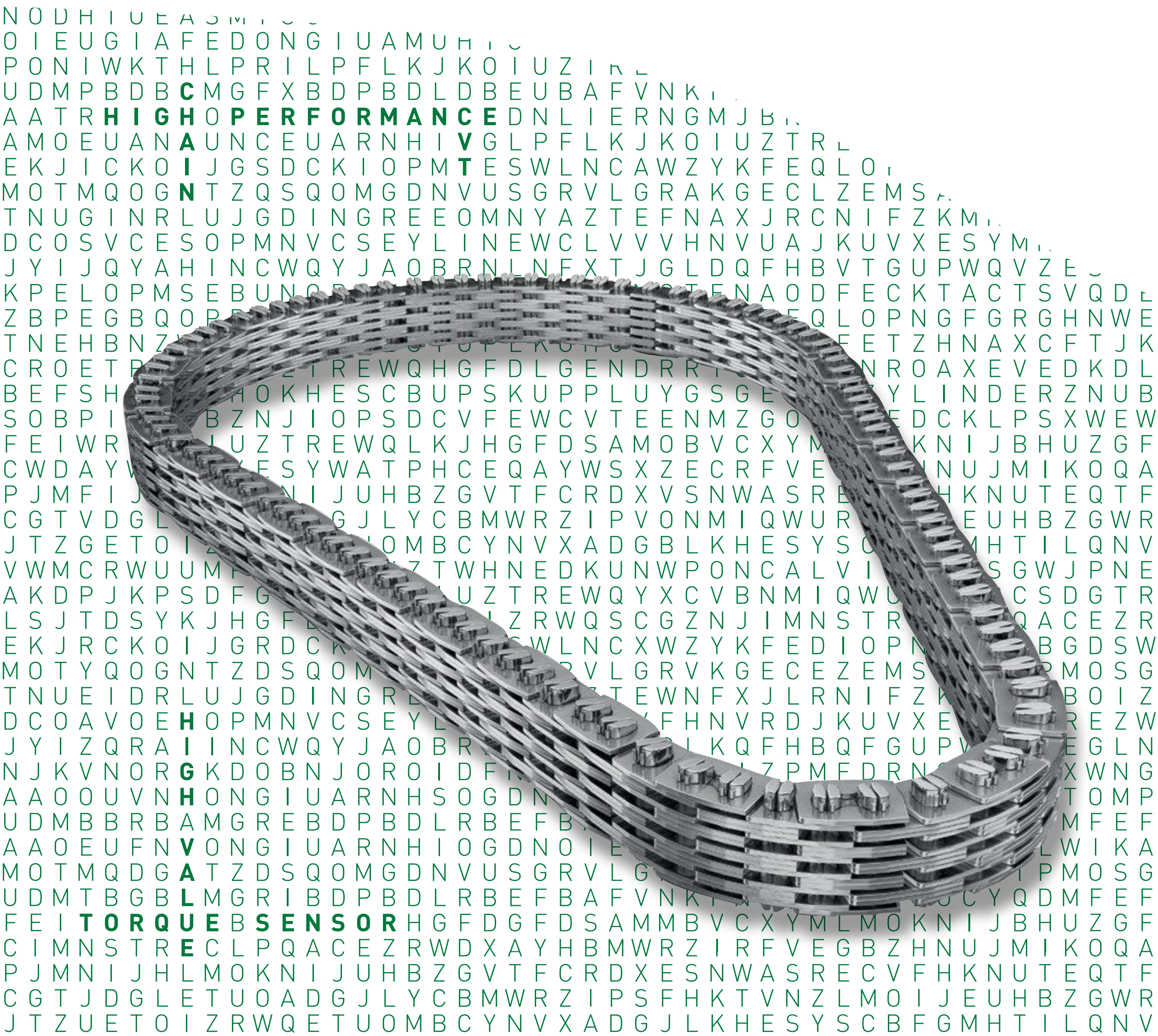
HIGH PERFORMANCE
CVT
CHAIN
HIGH VALUE
TORQUE SENSOR

CVT

The transmission concept of the future

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34

Introduction

Automatic transmissions are becoming more and more common in passenger vehicles and, at the same time, customers' demands for comfort and reduced fuel consumption are increasing. Optimized fuel consumption is very difficult to achieve with manual transmissions.

More than 20 % of automatic transmissions will be CVTs by the year 2020. A significant advantage in terms of fuel consumption can be achieved in operation at partial load, and hybrid concepts can be seamlessly combined with the CVT. The CVT can also be manufactured cost-effectively, and when combined with torque converters, modern damping systems, and hybridization, it offers a level of comfort that is difficult to surpass.

New chain types allow significant increases in ratio spread and strength to be achieved, a trend which future generations of chains will continue. In addition, the ratio spread can also be expanded through the use of gear stages/range shifting to include ranges that conventional automatic transmissions will have difficulty in achieving comfortably. This means that CVTs can support the trend towards downsizing and downspeeding with no problems. If required, the efficiency of the transmission can also be further optimized through the use of direct gear stages.

The CVT thus continues to represent one of the best technical solutions for the automation of the powertrain, particularly in the field of front transverse applications. Current developments and possibilities for further development will be looked at in detail in this paper.

Single-range and dual-range concepts

Aside from the actual specification, defining the concept is the most difficult task within the development process. Single-range and dual-range concepts are currently available on the market. Efficiency can also be further improved through the use of fixed-ratio gear stages. The choice of a concept essentially depends on the selection of the relevant components, such as the linking element, the clamping system, and the variator size. The quality of the overall concept in turn depends on the consistent optimization of the individual components in the transmission.

High Value CVT

The High Value CVT (HV CVT) concept [1] was presented in detail during the last Schaeffler Symposium and at subsequent symposia. This concept already preempted groundbreaking development trends: The weight was reduced to a minimum, the ratio spread was increased to values of more than 8, and hybridization was carried out with no modifications to the design envelope. The concept was designed in a modular fashion in order to fulfill the requirements of a wide range of markets, and continues to provide the same firm basis for further development. Previous publications have always illustrated the HV CVT in combination with a hydraulic-mechanical torque sensor. However, the HV CVT can also be implemented with electronically controlled clamping without a torque sensor if desired. Figure 1 shows a variation of this type with the designation HV CVT ec (electronic clamping)

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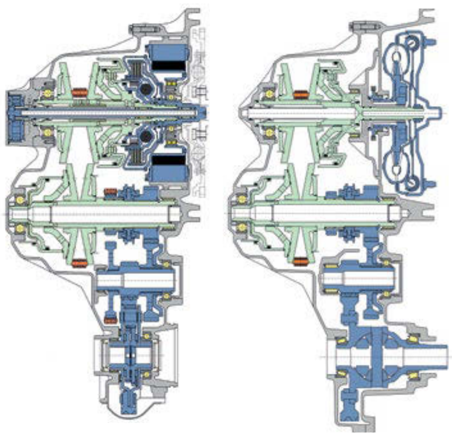

Figure 1 Comparison: HV CVT with torque sensor and HV CVT with electronic clamping

compared to the existing HV CVT. The advantages of the compact design and the variably selectable startup element can still be regarded as the main strengths of this concept. The reverse gear unit installed on the output side can also be combined with a conventional spur gear stage without a toothed chain and with a conventional differential, as desired. A cost-effective variant that is designed for optimized use of space is also possible when a LuK iTC torque converter [2] is used.

Single-range or dual-range structure

As indicated in the introduction, defining the concept is the most difficult task within the transmission development process.

In the past, a so-called "standard design" became the mainstay of CVT transmission concepts for front transverse applications (Figure 2). In this design, the pulley set on the drive side is installed directly on the crankshaft's axis and thus without an input gear stage. A planetary gear set with multi-plate shifting elements for reversing the direction of rotation is installed in front of this, and a torque converter is most frequently used as a startup element.

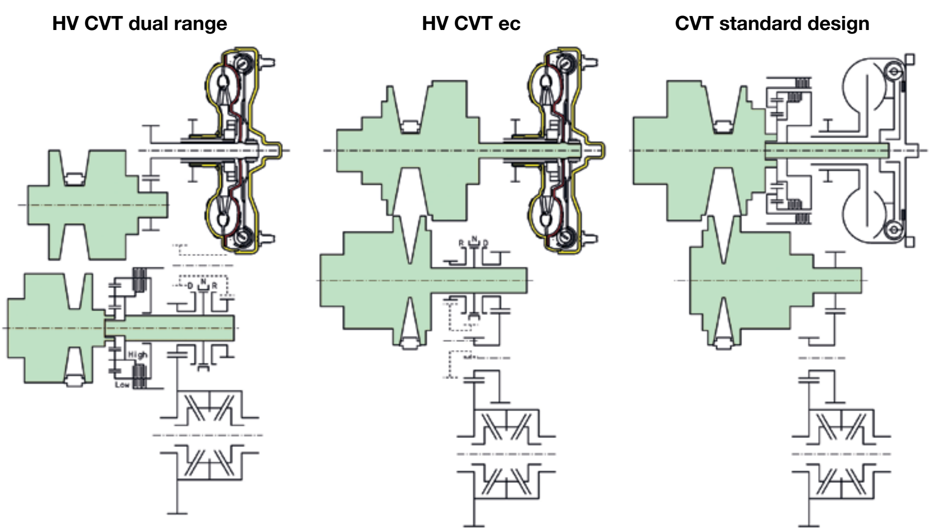

Figure 2 Comparison of CVT concepts for front transverse applications

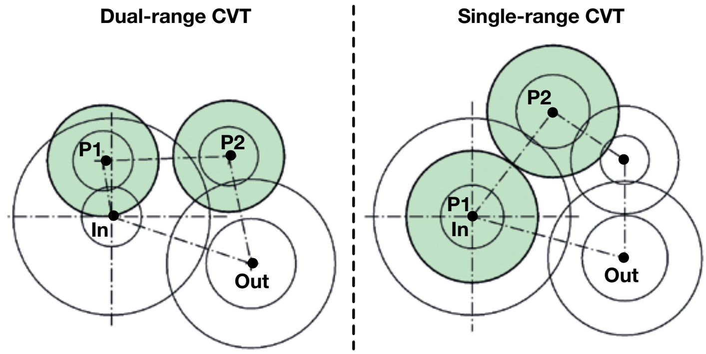

Figure 3 Cross-sectional view of dual-range CVT and single-range CVT

The HV CVT concept is the direct opposite. In the HV CVT, the assembly for reversing the direction of rotation is located on the output side and the cone pulleys arranged in mirror-opposite fashion. This provides a very compact arrangement with optimum use of installation space, particularly when combined with the LuK chain. The reverse gear installed on the output side also allows the transmission input range to be made very flexible with various startup elements. Most of all, hybridization is thus significantly simplified.

Jatco has now brought a dual-range CVT onto the market [3]. Because of the range shifting, there had previously always been a degree of skepticism about whether a dual-range CVT would be accepted by CVT customers who are accustomed to a certain level of comfort. However, Jatco has now successfully proved the skeptics wrong.

Figure 2 shows a sketch of the LuK HV CVT dual-range. This transmission design draft further simplifies the arrangement of the planetary gear set in comparison to that of the solution already on the market. Range shifting now only requires a single planetary gear set, meaning that this can also be easily and flexibly adjusted to various torque classes. The design-dependent input gear stage and the reverse gear installed on the output side in turn provide a higher degree of flexibility for the arrangement of a range of startup elements and for possible hybridization. The main advantage of the dual-range structure is that the variator can be dimensioned significantly smaller than in the case of a single-range CVT while maintaining the same gear ratio spread. In addition, ratio spreads of up to 10 are possible without the variator – and thus the transmission – having to be made disproportionately large. Figure 3 shows a comparison of the transmission cross-sections of a dual-range CVT and a single-range CVT (with their main axes) with identical gear ratio spread. The diameters of the cone pulleys are highlighted in color. The difference in the design envelope is clearly visible.

It can be summarized that a “standard design” CVT has the least suitable and least flexible design envelope with regard to future powertrains. In particular, this arrangement is the longest of the three concepts along the crankshaft axis, which is essential to the design envelope. Hybridization is difficult to achieve due to the planetary gear set for reversing the direction of rotation, which is installed on the drive side.

The two HV CVT concepts display comparable advantages in terms of length and the possibility of hybridization. The dual-range concept has the best cross-sectional arrangement. When it comes to costs, the outlay for the planetary gear set in the case of the dual-range concept must be compared to the additional outlay for the larger variator in the case of the single-range concept. The single-range concept proves to have a slight advantage here. The dual-range concept displays the greatest advantage in that larger gear ratio spreads can be implemented in combination with high torque capacity. There is no strict limit as to when it is better to implement a single-range or dual-range concept. A possible variation is presented in the next section with regard to this issue.

Modular front transverse variator system

The selection of a single-range or dual-range structure essentially depends on which total gear ratio spread has to be achieved at which input torque. High torques are essentially not a problem even with large gear ratio spreads when a LuK chain is used as the linking element. Sooner or later, however, the limit is reached when it comes to a competitive design in terms of design envelope, weight, and variator mass inertia. When a LuK chain is used, gear ratio spreads of up to 8.5 can be competitively achieved in a single-range system with no problems, even at high torques. This can be explained by the small minimum wrap radius that can be achieved and by the low height of the chain, among other factors.

The illustration of a front transverse modular variator system – using a LuK chain as the linking element – displayed in Figure 4 shows that, unlike competing transmission concepts, the design enve-

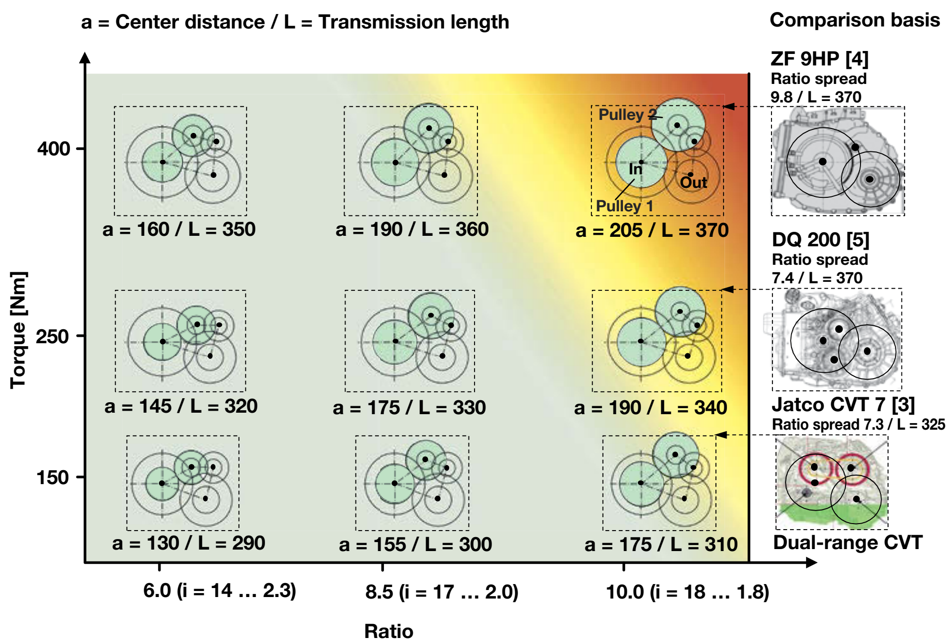

Figure 4 Modular front transverse chain variator system for a single-range structure

lope limits are not exceeded until gear ratio spreads of almost 10 are achieved. Of course, the higher the desired torque capacity, the faster the limit of competitiveness is reached. The yellow-to-red area represents a feasible dual-range structure variant for making the CVT competitive even with large gear ratio spreads. In cases such as special efficiency optimizations, however, a dual-range structure can also be advantageous with lower torques and medium gear ratio spreads with a chain as the linking element.

Figure 5 illustrates how the modular transmission system shown in Figure 4 changes when the range is implemented as a dual-range structure with a large gear ratio spread and a high torque.

It can clearly be seen that a CVT can competitively cover all ranges that are expected from front transverse drives. When the aspect of hybridization – which in the future will be universally in demand – is taken into account, CVT technology must be regarded as a ground-breaking transmission technology in the front-wheel drive sector.

Fixed-ratio gear stages

A further option for increasing efficiency is the introduction of a fixed-ratio gear stage. This variant offers a wide range of possibilities for further optimization. Numerous combinations of CVT variators with spur gear stages arranged in parallel have been brought onto the market in the past. In this case, however, we present a very space-

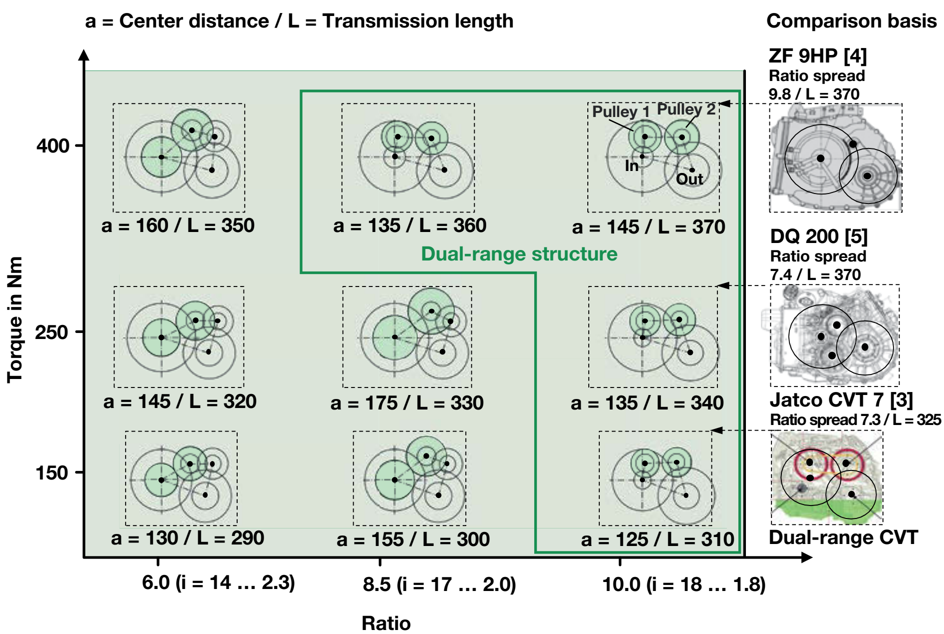

Figure 5 Modular front transverse system for a single- and dual-range structure

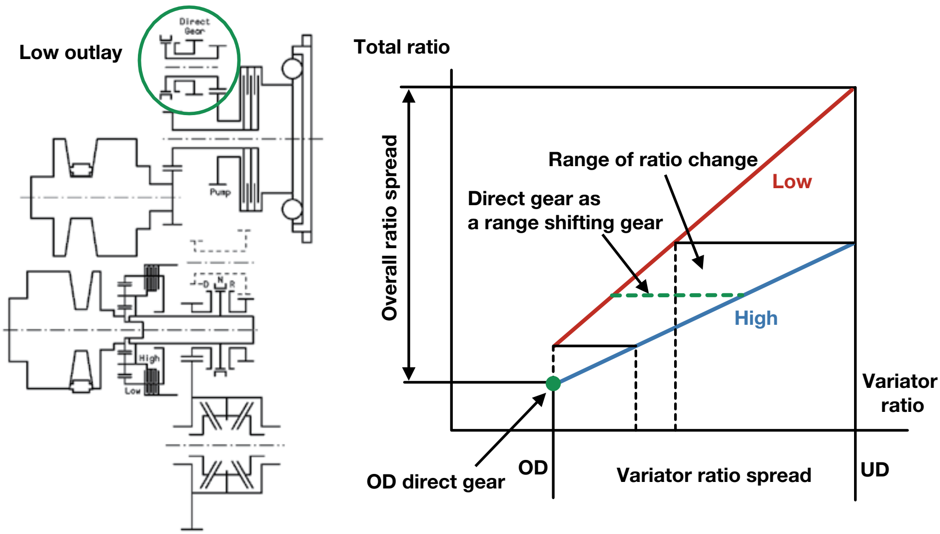

Figure 6 HV CVT dual range with direct gear stage

saving version that can also be used to allow the optimized use of an electric motor in a hybridized powertrain.

Figure 6 shows the implementation within a dual-range structure. In this case, the fixed gear ratio can be used either as an overdrive stage or as a direct shifting stage for range shifts.

The special feature of this design is that the spur gear stage, which is arranged parallel to the variator, is directly coupled with the engine damper and not in series behind the starting clutch or a torque converter. The direct gear stage can thus also be combined with the permanently driven pump gear stage, for example. In this arrangement, the direct gear stage requires almost no changes to the design envelope and only minimal additional outlay. The spur gear on the transmission's input side meshes directly with the large spur gear on the differential's output side here.

When used as an overdrive direct gear stage for the entire transmission, the spur gear ratio is selected in such a way that it can be engaged without a difference in speed using a dog clutch once variator overdrive has been reached. As soon as the flow of force has been closed via the spur gear stage, the variator can be completely decoupled in an efficiency-optimized way on the drive and output side. The intelligent use of route information (which will become increasingly comprehensive in the future) combined with current powertrain data means that this shifting operation can be carried out in a targeted way that allows it to remain unnoticed and is optimized in terms of fuel consumption.

The direct gear stage shown in Figure 6 can also be used as a range shifting gear stage. In order for the driver to notice the range shift as little as possible, the two operating ranges are implemented with a large overlap in today's applications. However, this leads to the loss of a large degree of overall ratio spread that, from a technical perspective, would actually be available. This can be made more effective through a range shift using a direct gear stage with an overall transmission ratio that remains the same – this is shown as a dashed green line in Figure 6. This allows the ratio ranges to be moved further apart and thus a larger overall ratio spread to be achieved without a larger variator. During the range shift, the drive energy is transferred to the differential via the direct gear stage with no dips in the tractive force. Meanwhile, the variator can be moved to the new range with no load. The engagement/disengagement of the direct gear stage can be carried out using a dog clutch without being noticed by the driver, as there is no difference in speed at the shifting element. When fast downward shifting ("kick down") is desired within the high-ratio range, it is also possible to jump vertically to the low-ratio range without using the shifting gear stage. The engine speed is adjusted here using a multi-disk brake operated with slippage, which means that even spontaneously desired ratio shifts can be carried out quickly.

High Value CVT multimode

Numerous facts that support the use of a CVT in front transverse powertrains have been illustrated by the innovations presented in the previous sections and by the modular CVT variator system presented here. The aim of the following section is to illustrate a transmission concept variation that takes these innovations as a starting point and provides groundbreaking possibilities with regard to hybridization.

The transmission variation known as the "High Value CVT multimode" is illustrated as a dual-range concept in Figure 7. The outlay for the planetary gear set for range shifting on the output side was further reduced in comparison to the High Value CVT dual range. Now, only a multi-disk brake is integrated for shifting to the low range. Because a direct gear stage is provided for range shifting (as described in the previous section), the shift to the

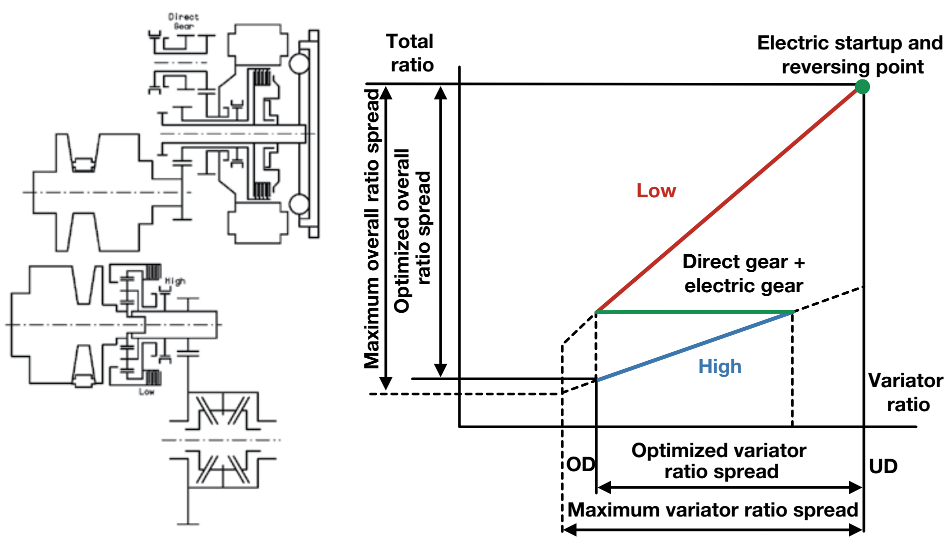

Figure 7 HV CVT multimode

high range can be carried out using a dog clutch.

The use of a direct gear stage for shifting between ranges also allows the variator to be utilized more effectively. It is possible, as illustrated by the dashed line in Figure 7, for the variator's utilization range to be limited in comparison to the current state of the art in overdrive while retaining the same overall transmission ratio, which means it can be operated with more optimized efficiency. The overall gear ratio spread could also be further expanded or the variator further miniaturized, however.

The concept is hybridized. Reversing is completely ensured by the integrated electric motor (a dedicated mechanical reverse gear is intentionally omitted for reasons of installation space, cost, efficiency, and comfort). To safeguard the functionality of this design, the hybrid battery can even be charged by the internal combustion engine via the electric motor when the vehicle is stationary.

The illustrated transmission architecture additionally offers a wide range of operational possibilities:

- The electric motor can be used to drive with optimum efficiency via the direct gear stage when the CVT variator is completely decoupled and stationary.
- When braking, energy can be recovered via the direct gear stage – and thus when the internal combustion engine is decoupled – without an additional K0 being required.
- The electric motor and the internal combustion engine can be operated in parallel at different speeds via the direct gear stage and the CVT variator, respectively.
- The electric motor can of course also be operated via the CVT variator. For electric starting when a large wheel torque is needed, it is planned that the variator should be operated at the UD end stop, thus utilizing the entire available transmission ratio.
- Finally, the electric motor can be used to boost the internal combustion engine via the direct gear stage while driving at maximum torque without the chain variator being subjected to any additional load.

Despite these numerous functions and operating modes, this hybrid transmission concept can be made more compact than a CVT in standard design without a hybrid motor or transmission of a different type. This new transmission concept also offers possibilities for gear ratio spreads of up to 10 in all common torque ranges. Compared to other hybrid transmission concepts with the same functionality, a result that is also attractive in terms of costs is to be expected.

Chain 05 – the next generation

The CVT chain has been undergoing constant further development over the last few years, which has made it possible to continuously increase its performance density. It was possible at the same time to retain the positive characteristics, such as the excellent level of efficiency. The latest measurements indicate that this efficiency level is up to 4 % higher (depending on the operating point) than that of comparable linking elements from our competitors. Significantly higher overall gear ratio spreads can also be achieved with this chain, which means that the overall efficiency of the powertrain can be further improved as explained earlier. Because of the chain's good scalability, higher torque applications – particularly in combination with powertrain hybridization – can be achieved with a long operating life. Figure 8 illustrates the torque capacities of the different chain types.

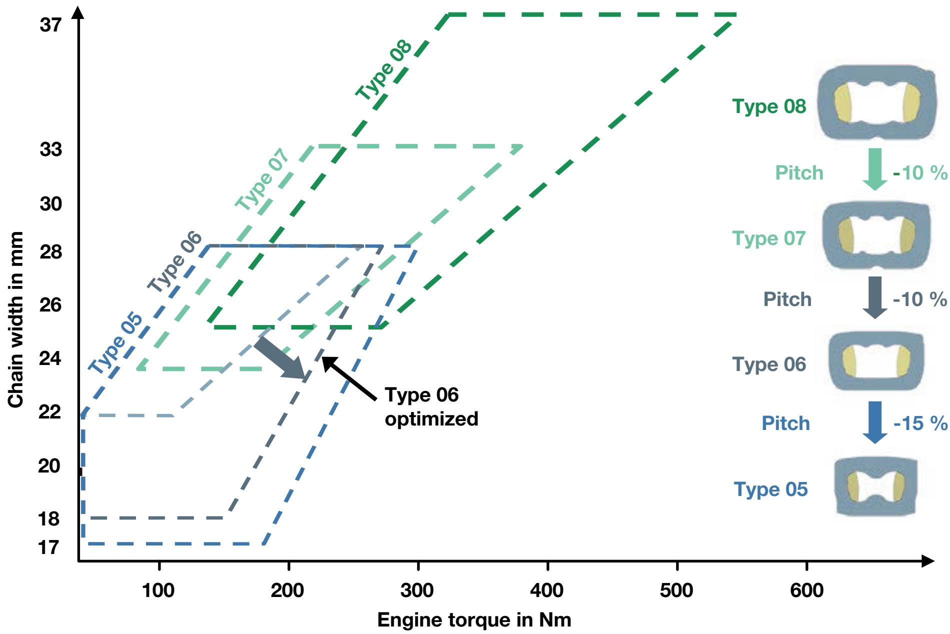

Figure 8 Torque ranges of the different chain types

The application of the chain in smaller vehicles, however, requires a further improvement in the chain's acoustics in order to reduce the outlay in the vehicle to a minimum. The chain's pitch is a variable that has a major effect on the acoustics. The aim was therefore to develop a new generation of chains with a pitch that is reduced by a further 15 % while retaining at least the same torque capacity compared to type 06 [1].

Optimized acoustics through reduced pitch

The reduction of the chain plate pitch over the course of each new chain generation (08 > 07 > 06) has allowed the chain's acoustics to be significantly improved. The lower the pitch of the chain, the more links are present in the same length of chain and the lower the speed at which each link comes into contact with the pulley set. The impulse of impingement becomes lower as the number of links in the chain's length increases (see Figure 9).

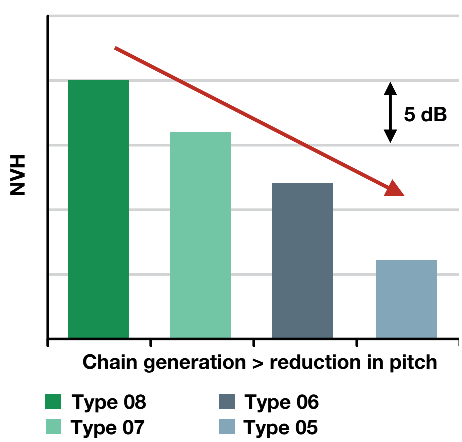

Figure 9 Reduction of noise emissions as the pitch is lowered

In order to further utilize this effect, the 05-generation chain was developed, with which the pitch is reduced by a further 15 % compared to the 06-generation chain.

Only as strong as the weakest link

The requirements for the "small" 05-generation chain were ambitious. It had to achieve the same degree of strength as the 06-generation chain while likewise maintaining the smallest possible running radius and without falling below the outstanding efficiency level of its "bigger brother".

How is it possible to support identical or even higher loads using chain components that have a smaller cross-section? The key to achieving this is an in-depth understanding of the stress processes to which the components are subjected. For this purpose, some entirely new calculation tools were developed that determine the damage to the components with even greater precision and facilitate their optimization.

In simple terms, the new calculation tools determine the exact stresses placed on the components in the weakest chain link that are subjected to the highest load, and these are then applied in calculating the damage to the components. In addition, the changes to the components due to the manufacturing processes are taken into consideration.

Confirmation by measurement

During the development of the new calculation methods, a temporary version of the procedure was used in order to evaluate a relatively simple optimization of the existing 06 geometry. This produced a calculated damage reduction of approximately 38 %, which was inspected using a high-load underdrive test (strength test in the startup ratio). The B10 value of the measured chains was approximately 4.8 times higher than that of chains with no geometrical changes, which already made a convincing case due to their good running time results (see Figure 10). The calculation results were therefore confirmed.

These new calculation methods mean that it is now possible to determine the optimum geometry. Figure 11 illustrates the comparison between the existing 06 generation and the initial prototype of the 05 generation.

The obvious course of action is to transfer the new design ideas to the existing larger chain variants. This will make it possible for applications that today are equipped with a 08 pitch to be operated with an optimized 07 chain in the future.

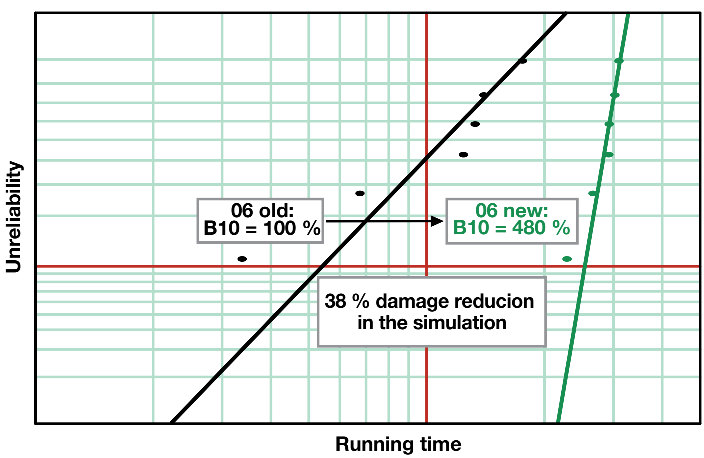

Figure 10 Results of continuous underdrive tests on the 06-generation chains

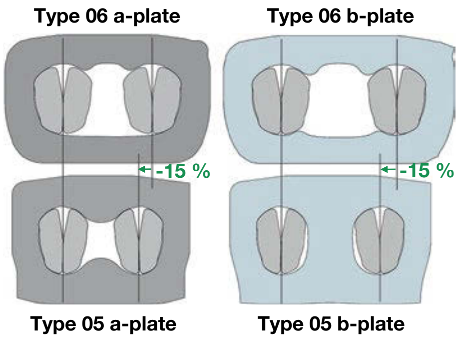

Figure 11 Comparison of the 06 and 05 chains with adjusted geometry

Targets far exceeded – improved acoustics with a longer operating life

The loads of the 05 chain were simulated for an existing customer transmission application with a maximum input torque of 250 Nm. The calculations show a 21 % reduction in damage compared to the previously critical point. If the relationship between the damage reduction and the actual operating life is similar to the values from the aforementioned underdrive tests with the 06 chain, a significant increase in chain strength is to be expected.

At the same time, the mass distribution over the chain's length was optimized. Previous tests have shown that it is possible to further improve the acoustics of the chain by homogenizing the mass over the chain's length. The previous long-plate links have a lower relative mass in relation to their length than the short-plate links. It was possible to optimize the mass distribution over the length of the chain by filling in the center area of the chain plates (Figure 11). The maximum mass difference over the length was approximately 14 % for the 06 chain, which was reduced to 12 % for the 05 chain. The implementation of the 15 % smaller pitch and the improved mass distribution means that a significant improvement in the chain's acoustics is achieved.

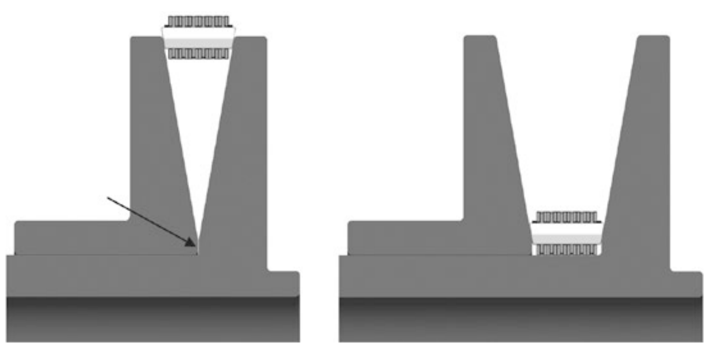

Figure 12 Limitation of the smallest chain width by the pulley geometry

The potential of narrow 05 chains

The minimum width of a chain is limited by factors such as the pulley geometry. The pulley angle and the dimensions of the pulleys define the smallest possible chain width. Figure 12 illustrates an example of the how the pulley geometry limits the smallest chain width.

A test was carried out using an existing CVT application in the 140 Nm class to discover how high the maximum transferrable torque would be with the smallest possible 05 chain. For this purpose, the smallest chain width at which the pulleys do not quite reach their end stop when the gap is closed was determined for the stated transmission application. This produced a chain width of 17.5 mm. Chain calculations indicate that a “narrow” chain of this type would allow not only the calculated application to be carried out but also that up to 180 Nm could be transferred in underdrive.

The use of a narrow chain saves weight

The 1705 chain is approximately 7 mm narrower than a 24 mm push belt and a 2406 chain. A weight saving of more than 300 g is achieved in comparison to the push belt, and a saving of 70 g is achieved even in comparison to the 2406 chain. Figure 13 illustrates a size comparison between the 1705 chain and a 24 mm push belt.

A narrower chain affects the design envelope and the overall weight of the transmission, however. In comparison to a small CVT with a 24 mm push belt, weight savings of up to 650 g are conceivable on the pulley sets, the linking element, the aluminum housing, and small components.

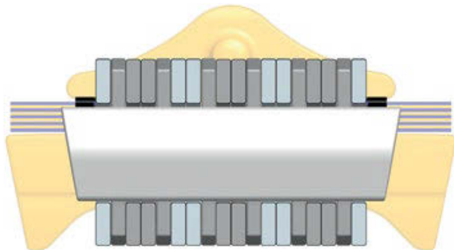

Figure 13 Comparison of a 1705 chain and a 24 mm push belt

Summary

The High Value CVT concept continues to make a convincing case due to the modularity of the system when it is combined with a chain from the new 05 generation. The new generation of chains has a 15 % smaller pitch and a higher torque capacity than the 06 generation. Even single-range transmissions can achieve very high ratio spreads with these chains. In dual-range transmissions, the size of the variator can be significantly reduced for ratio spreads of up to 10. This brings with it additional benefits in terms of weight and with regard to mass inertia reduction.

The High Value CVT multimode concept shows further possibilities for increasing the efficiency and functionality of the CVT. Improved hybrid technology is possible with a reduced outlay in comparison to other transmission concepts.

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