1 Introduction

Since their introduction a few years ago, dual clutch transmissions have enjoyed a good reputation by combining the comfort of a step-automatic with the high effectivity of a manual transmission. They are perceived to be both sporty and efficient, which is why the development of this type of transmission has a high priority with almost all automotive manufacturers. The success of the dual clutch transmission has been made possible by greatly improved electronics - the dual-clutch principle is after all nothing new: in the 1980s some motor sport teams used this technology to their advantage. In 2003 Volkswagen refined the dual-clutch technology for serial production.

The innovative dual-clutch technology plays a major role in this concept: it has a decisive influence on comfort and efficiency. In the dual clutch itself the lamellar packs, their positioning and in particular the actuating spring elements for clutch return are of particular importance. Disc springs can save considerable space – particularly axial – compared to coil spring packs; further, their other properties can offer additional benefits, such as superior stability against centrifugal forces.

Slotted disc springs – i.e. springs with “fingers” on the inside – have been well established with step automatic transmissions since the mid-Nineties, as they opened up the possibility of a horizontal load curve in addition to the advantages mentioned above. However there are apparent drawbacks such as hysteresis or excessive deviations in production as far as the height of the fingers is concerned. This often leads to slotted disc springs not being considered in the advanced development phase. Further, dual clutch transmissions are still new to the market and designs will mature in time. Many of the parameters important for development engineers were simply not known to the disc spring manufacturers. Mubea has studied these special requirements and offers disc springs targeted at dual clutch transmissions.

2 Advantages of disc springs in automatic transmissions

Both with classic automatic transmissions and modern dual clutch transmissions the switching elements take up a significant amount of the assembly space available and are therefore of interest to the design engineers. For a compact design, one of the few ways to save both radial and axial space is in the choice of piston return springs. Disc springs are used in modern automatic transmissions for piston return in the clutch. The essential advantages as opposed to conventional coil spring packs are the lower axial space required as well as great flexibility in the load curve. The saving in installation space often leads to a reduction in the overall system cost, resulting in further cost reduction potential.
2.1 Improved Installation Space (vs. Coil Spring Packs)

Disc springs used for piston return require less axial space, so savings can be made both in the length of the clutch as well as the overall length of the transmission, if disc springs are included in the early development stages of the transmission.

This was verified in a recent benchmark. An automatic transmission, in serial production with coil spring packs, was redesigned with disc springs for piston return. Figure 1 shows the savings achieved in space, weight and cost compared to using coil spring packs.

In this example the length of the clutch could be reduced by approx. 11%. The benefits for the whole transmission depend on the overall packaging and were quantified in this example with a reduction in length of 3.6%.

In this concept study, the saving in length resulted in a weight reduction of 3.4% (= 1.7kg). Assuming that material accounts for approx. 50% of the total transmission cost, material costs were reduced by 1.7% (= $ 25.50 with total transmission cost of $ 1,500). It was assumed that the substitution of coil springs with disc springs is cost neutral; however, the disc springs replace not only the coil springs but also the brackets and retainers.

An additional positive aspect of disc springs affects the vibrational behavior of the transmission. The lighter and shorter design results in higher Eigenfrequencies, both vertically and horizontally, thus reducing noise and vibration whilst driving. In this case, a 4-cylinder engine was studied and the frequencies of the disc spring version lay above the normal engine frequency when driving in the 2000-5000 rpm range.

Fig. 1: AT improvement by reduction of clutch length
2.2 Horizontal Load Curve Characteristics

As well as enabling a compact design, transmission disc springs offer an additional functional advantage. As opposed to coil spring packs, which always have a linear load curve, slotted disc springs can achieve a mainly horizontal load curve if desired. The spring load can be kept constant during the stroke (working range), i.e. between E.H (engaged height) and spring height at closed clutch including wear F.L.H. (fully loaded height). In spite of the somewhat higher manufacturing tolerances required for disc springs (standard wise +/- 10% compared to +/- 6% for coil springs), this results in a significantly lower load difference between the two working points E.H and F.L.H (Fig 2). In addition, tighter load tolerances can be kept for specific working points if desired.

![Graph](image)

**Fig. 2: Improvement of shift quality by optimized load characteristic**

This leads to a big advantage with respect to gear change, particularly with the control of the hydraulic system. The spring load is constant, regardless of the actual position of the piston in the engaging range, and the oil pressure can be controlled within a much smaller range, as less hydraulic pressure is required due to the lower load difference between E.H and F.L.H. In this study, the hydraulic pressure required for torque transmission could be reduced by 60Kpa, leading to an improvement of more than 0.2% in total efficiency at the F.L.H. point.

2.3 Radial Rigidity at High Revolutions

A further benefit offered by disc springs as opposed to coil springs is the high shape retention and stiffness against external forces. This is particularly noticeable at high clutch revolutions, which lead to high radial centrifugal forces. The single coil springs have a tendency here to "bulge out" radially which has a negative impact on performance. Mubea disc springs are not affected due to high revolutions.
3 Dual Clutch Transmission Concepts

The dual clutch in DCTs nominally has the same functions as conventional clutches in manual transmissions. The transmission consists of two partial transmissions which are independent of each other. The main difference however is that a separate friction clutch is allocated to each partial transmission. The friction clutch ensures the power flow from engine to transmission. The next gear is already pre-engaged in the other partial transmission: all that needs to happen is that one clutch opens and the other closes, which allows for a much quicker gear change.

As shown in Figures 4 and 5, it is possible to choose varying relative positions for both clutches, i.e. radial or axial, depending on assembly and packaging requirements. Both alternatives have design advantages and disadvantages.

One advantage of the radial positioning of the lamellar clutch packs is the short axial installation space. The outer clutch has a significantly higher performance due to the higher middle frictional radius. The additional radial space required and poorer cooling can however be disadvantageous.

Both clutches perfectly can be adapted to the specific necessary demands and an oversizing can be avoided. So this arrangement results into a lower drag torque of the clutch that is currently not active and therefore into shorter possible reaction times and an improved spontaneity.
Fig 4: Radial clutch concepts
left: coil springs only; middle: outer clutch disc spring, inner clutch coil springs; right: disc springs only

The advantage of axial positioning is the symmetrical construction of the clutches with fewer components and lower costs. It is also easier to calibrate the clutches, which have a greater adaptability, e.g. when the same dual clutch is to be used with different types of transmissions. The disadvantages are the same as the advantages of the axial positioning: one of the clutches is always going to be over-sized.

Fig 5: Axial clutch concepts
left: coil springs only; right: disc springs only
Both clutch types have to comply with the general requirement to be as compact as possible, whereby the strengths of one show up the weaknesses of the other. Mubea disc springs can have a positive influence here. With radial positioning, which hardly leaves any room for coil spring packs underneath the lamellar clutch packs, the advantages of disc springs are clear. This is well demonstrated in the first 6-gear DSG on the market from Volkswagen: Mubea disc springs are used for the outer clutch, whereas a coil spring pack is used for the inner clutch, which has more space underneath.

But also axial positioning – which presents design challenges due to the amount of axial space required – can be improved by using disc springs. The total length of the transmission can be reduced by moving sideways-positioned components towards the centre of the clutch. However only disc springs with the smallest possible outer diameter can be used, which can cause problems with stress. Mubea can meet this challenge with a new technology which increases the lifetime: this technology is explained in the following section.

4 New Demands by DCT Regarding Function and Production Tolerances

4.1 New Deep Rolled Disc Springs for Reduced Installation Space

To meet these requirements, Mubea developed its Generation II disc spring. Due mainly to a significantly improved residual stress curve, the disc springs can be stressed much more than previously which gives more scope in the design.

Fig. 6 shows a typical residual stress curve resulting from the conventional production process. The residual stress is measured just under the disc spring surface and the curve is a result of the shot peening and pre-setting processes. This can be compared to the residual curve for Generation II disc springs. As can be seen, this has much higher residual stresses which penetrate much further beneath the spring surface.

![Residual stress curve](image)

Fig. 6: Compressive residual stresses due to shot peening and deep rolling
A known technology from other applications was used to make this possible: deep rolling (Fig. 7). This deep rolling process causes a local material flow in the surface layer due to a high Hertzian Pressure. It is characterized by a defined rolling force, which remains constant, more or less independent of peripheral conditions.

Fig. 7: Principle of deep rolling for disc springs

Deep rolling has a considerable effect on the lifetime of the disc springs. Din 2093 provides specifications for lifetime relative to material thickness as shown in Fig. 8. Mubea already exceeds the Din 2093 requirements with the current production process. By using Generation II, however, the lifetime can be greatly increased.

Fig. 8: S/N diagram for disc springs
The disc springs show the highest tensile stresses under load on the bottom side and partially on the side edges tangentially at the inner and outer diameter. Depending on the ratio between spring height and material thickness the greatest tensile stresses lie either at the outer diameter, inner diameter or are evenly distributed over the whole bottom surface. The deep rolling process with disc springs is applied in accordance with the distribution of tensile stresses. Disc springs are particularly suited to deep rolling because of their symmetrical shape. The amount of load stress and the gradient over the ring width defines whether the disc spring is totally or partially deep rolled. The feed movement depends mainly on the diameter of the ball in the deep rolling tool.

Thus Generation II disc springs result in a significant reduction in radial installation space. Depending on the application, these springs require about 15% less diametrical installation space.

The additional production costs caused by deep-rolling are normally compensated by the considerable reduction in installation space required, which in turn leads to a reduction in transmission size and weight. The actual cost saving differs from case to case and therefore cannot be given here. However the savings can be considerable, particularly when the size of the piston return mechanism was critical to the overall size of the transmission.

4.2 Load curve with Positive Gradient

As described in Chapter 2.2, slotted disc springs offer the possibility of a horizontal load curve in the engaging range. For many automatic transmissions this has the benefit of lower oil pressure in the system. However this is often not desirable for dual clutch applications. Instead the disc spring should show an increasing load curve, in order to provide feedback for the piston position via the forces playing on the piston.

By influencing the \( h_0/t \) ratio, i.e. the ratio of the Belleville type spring ring to material thickness, disc springs can provide line curves either with a saddle point (ratio \( h_0/t = \sqrt{2} \)) as well as climbing load curves (\( h_0/t < \sqrt{2} \)). The ratio \( h_0/t > \sqrt{2} \) produces an s-formed load curve, climbing strongly at first and then descending during the stroke.

Fig. 9: Load curve with positive gradient (theoretical and measured)
4.3 Elimination of Spring Height Deviations due to Mubea’s Optimized Production Process

High quality disc springs are standardized in line with DIN 2092 and DIN 2093. Mubea has optimized the production process beyond DIN 2093, particularly as far as higher geometric precision is concerned.

In particular, the hardening and tempering processes were developed by Mubea for use in automatic transmissions, thus making it possible to use highly stressed disc springs with tight tolerances in automatic transmissions. Especially the roundness could be optimized significantly due to this new process. The application in dual clutch transmissions is made more challenging by the increased specification with respect to the height deviations when looking a the spring side wards, i.e. the need for uniformity in the height of the single fingers.

![Fig. 10: Sketch of spring finger height deviations](image)

The clutch unbalance is made up of production deviations of the components which come into contact with each other, i.e. the spring as well as the piston tolerances. This clutch unbalance causes undesirable dynamic deviations in torque. This disturbance in torque is an irregularity in momentum which is superposing the average torque. It is particularly noticeable during low stress periods, i.e. when driving off in the vehicle, whereas during starting with more power, other causes play a role.

Whereas in torque converter automatic transmissions this production tolerance parameter has a negligible impact on driving and gear change comfort, it is of considerable significance to dual clutch transmissions.

Starting with a torque converter AT entirely happens hydro-dynamically by use of the torque converter and the lock-up clutch in the torque converter is completely open, the clutches in the transmission closed. The clutches in this type of transmission are purely shift clutches whose open and close functions are controlled.

With dual clutch transmissions on the other hand, the high gear ratio in first gear means that even the slightest moment disturbance in the clutch has a negative impact when driving off, with a perceivable longitude vibration in the vehicle.

Fig. 11 shows measured irregularities of momentum in disc springs with differing quality of height deviations of the spring fingers.
Irregularities of momentum (blue) due to disc spring with maximum finger height deviation of ~0.4mm

Fig. 11: Irregularities of momentum

Legend:
- green = pressure ramp
- light blue = momentum ramp
- dark blue = irregularity of momentum
- red = rpm
- x-axis: time in seconds

With kind permission of ZF Sachs AG

In order to achieve a finger height deviation as low as possible, production tolerances of functional and geometric dimensions must be kept as low as possible.

Starting with cold rolling, all production steps are done in-house. Following splitting, the blanks are fineblanked. 5-modular flat deburring machines ensure high-precision and top quality deburring.

The tempering process consists of an automated process chain of austenizing, quenching and forming in a water-cooled tool, followed by tempering. The precision and process stability of shot peening has been greatly improved by using specially designed feed-through type equipment. After pre-setting, whereby each spring is pre-set in line with its individual strength, each spring is checked for surface defects and damages before being packed and dispatched to the customer.

The process steps which have the greatest influence on the inconsistent height of the spring fingers are hardening and shot peening. In general, the inconsistencies resulting from the hardening process mainly result in an elliptical distribution whilst those resulting from shot peening are more random and distributed less uniformly.
In the following, both process steps and measures introduced by Mubea are described.

4.3.1 The Mubea Hardening process for transmission springs

The tried and tested Mubea hardening concept, which has been used for years mostly for piston return springs in automatic transmissions, provides the best pre-conditions to avoid hardening distortions, which can occur during the quenching process. The result is more consistent geometric precision than with standard tempering processes.

This is achieved by a process chain (Fig. 13) in which the austenitized hot springs are simultaneously quenched and coined in a water-cooled tool. As opposed to tempering in a salt or oil bath the springs cannot retract during the quenching process due the calibration in the tools.

The main reason for the previously described elliptic distribution of height deviations is that the springs are not located exactly centrally in the tool when this closes. Even hundredths of a millimeter can play a major role here. For use in dual clutch transmissions, various design improvements were therefore made to the tooling whereby the ellipse could all but be eliminated.
4.3.2 The Mubea shot-peening concept for transmission springs.

To enable the customer to take full advantage of tight tolerances, it is important that the extraordinary flatness of the hardened springs – achieved by the Mubea hardening process – is maintained in the following production steps. Shot peening in particular can negatively impact the flatness of the springs.

Due to the high volumes and small dimensions involved, transmission springs are usually shot peened in bulk in roto-drum blasting equipment. The particles are accelerated by the gravity of the drum, which continuously spins the springs. In spite of both the intensity of the steel shot treatment and saturation rate being kept constant and controlled throughout the process, the drawback of this process is that each part is not uniformly coated by the shot peening particles. This can cause increased deviations in the height of the spring fingers. These are mainly random deviations and are less uniform than those previously described and which were caused by the hardening process.

One aim of the new Mubea shot peening process is to keep the saturation and Almen intensity as consistent as possible over the entire surface of each part. This mostly avoids height deviations, leading to less differences in height. A further positive effect is that the differences in a bigger batch are fewer due to a more uniform coating, which further reduces the load tolerances per batch to a minimum.

The equipment (Fig. 14) still works on the turning wheel principle, however each spring is guided individually through the ray-spot using constant parameters. This allows uniform surface treatment for each spring as well as consistent processing of a whole batch.
The measures outlined for these two process steps – but also for others – led to a significant reduction in height deviations of the spring fingers (Fig. 15). In some cases, a specific boundary value was agreed with the customer. This is tested 100% during production using laser measuring equipment and special software, thus ensuring the required quality for each disc spring.

**Piston return spring with small finger height deviation < 0.1mm**
Measurement of finger heights by dial indicator gauge on 18 fingers

After optimization

Fig 15: Minimum height deviation of spring fingers due to optimized production process.
5 Current Application examples

In 2003, Dual Clutch Transmissions made the breakthrough into serial production with the Volkswagen Golf R32 and Audi TT. Volkswagen and BorgWarner developed this wet-running system with the internal code DQ250 for torques of up to 350 Nm. For DQ250 BorgWarner, as DCT supplier, positioned both lamellar clutch packs radially and utilized Mubea disc springs for the outer clutch to reduce installation space (Fig 16). Mubea has since delivered 1.5 million of these piston return springs.

![Fig 16: DQ250 Double Clutch Transmission, so-called DSG® from Volkswagen](http://www.volkswagen.com/vwcms/master_public/virtualmaster/de2/erlebnis/innovation/Technik_Lexikon/6-Gang-Doppelkupplungsgetriebe_DSG.html)

The first dual clutch concept with disc springs for both clutches was developed by ZF Sachs and went into serial production in 2008. Both clutches are radially positioned: in the outer clutch a single disc spring is used, similar to DQ250. The piston in the inner clutch is returned by two identical springs in a stack (Fig 17). In this way the load is doubled, with the stroke of a single spring and only a minimal increase in length (in this case the material thickness of one spring). Thus, the actuators could be placed beneath the lamellar clutch pack, which enabled a very slim design, in spite of high load requirements with the small diameters available.
Hoerbiger / Getrag is pursuing a totally different concept for returning or opening the clutch piston. The single friction plates are separated by placing separating disc springs as disc springs with a thin ring thickness. The big advantage of this concept is that the drag torque, which occurs in the clutch currently not being closed, is significantly reduced.

Furthermore the reduction of drag torque after shifting is significantly accelerated which results in a further optimized reaction time and spontaneity. These disc springs have been supplied by Mubea since the DCT was brought onto the market, e.g. in the Ferrari California.
Apart from the DCTs already in production, there are other applications with Mubea disc springs, which are still in the development phase. Some of them include the above mentioned concepts with axial clutch positioning, where the disc springs are placed under the lamellar clutch packs to save space or further concepts with separating springs between each of the friction plates. Confidentiality agreements with the customers prevent any details being divulged during the development phase.

6 Conclusion

Slotted disc springs have successfully established themselves in step automatic transmissions since their introduction in the mid-Nineties. Their low requirement of installation space makes a compact design possible. Further, they offer functional advantages due to the potentially horizontal load curve and good performance at high revolution.

Dual clutch transmissions can also benefit from these advantages. Design-wise, the clutches can be positioned either radially or axially. In both cases, disc springs can make a significant contribution to saving space.

Inconsistencies in production, particularly of the finger height, often meant that disc springs were not considered for dual clutch transmissions, which place higher requirements on the springs. Mubea solved this problem so disc springs can also be used in dual clutch transmissions. With the improved hardening concept, the completely new shot peening process and in particular the Generation II technology, Mubea disc springs now offer perfect conditions for use in dual clutch transmissions.

Dual clutch transmissions already in production and various development projects show the potential which is now offered to development and application engineers for piston return movement.