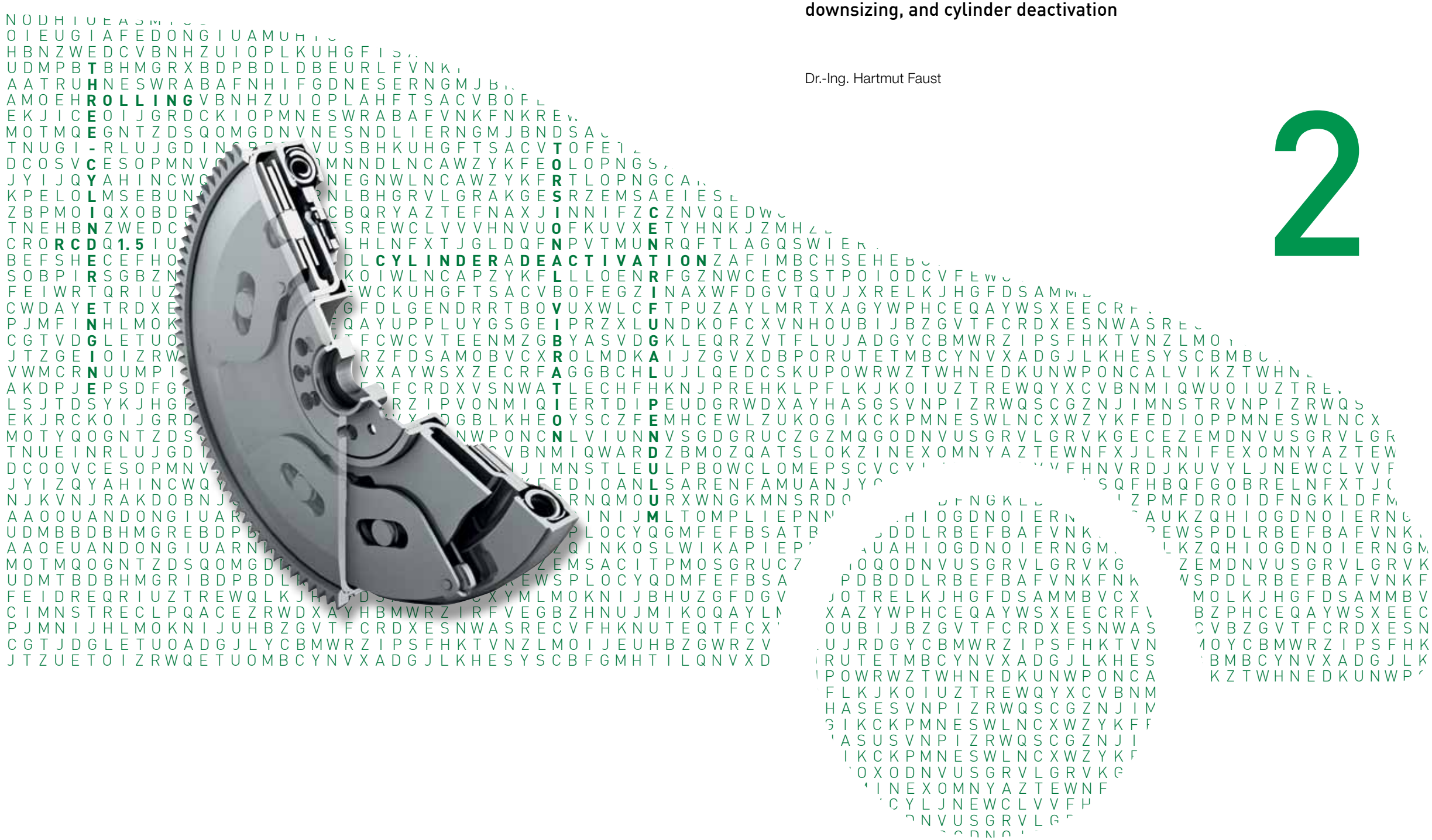

Powertrain Systems of the Future

Engine, transmission and damper systems for downspeeding, downsizing, and cylinder deactivation

Dr.-Ing. Hartmut Faust

2

Introduction

Besides hybridizing the powertrain, which is especially advantageous in city traffic, efforts must be made to improve the efficiency of conventional powertrains in order to reduce traffic-based CO_2 emissions.

This will first require measures to directly reduce friction losses in internal combustion engines, transmissions, and chassis systems, such as the use of friction-optimized bearing supports and seals as well as coatings to lower the friction coefficient.

Furthermore, slippage losses in startup elements need to be reduced. Hydrodynamic torque converters with lock-up clutches are a notable example of this, as they can be engaged even at very low engine speeds by means of optimized damper systems. Double clutch systems with reduced passive clutch drag torque losses of wet or – even better – dry running design are important contributions as well.

The aim of this paper is also to report on improvements to the system as a whole, in which changes on the transmission side lead to an efficiency increase in the internal combustion engine. Examples of this include transmissions with an increased spread of gear ratios, resulting in lower engine speeds even at higher travel speeds [1]. Optimized damper systems serve to further reduce and/or insulate torsional vibration excitation introduced into the entire powertrain by cyclical combustion in the engine and facilitate downspeeding of drive systems in order to reduce fuel consumption.

At the same time, advanced damper systems permit the design of downsizing systems that reduce engine friction with a lower number of cylinders and substantially increased torsional vibration excitation without having strong NVH issues in the entire powertrain. Finally, a rolling cylinder deactivation system is introduced that enables engines with three cylinders to run effectively on 1.5 cylinders ("RCD 1.5"). The measures taken on the engine and transmission system side to prevent excessive torsional vibrations along the entire powertrain are described in detail.

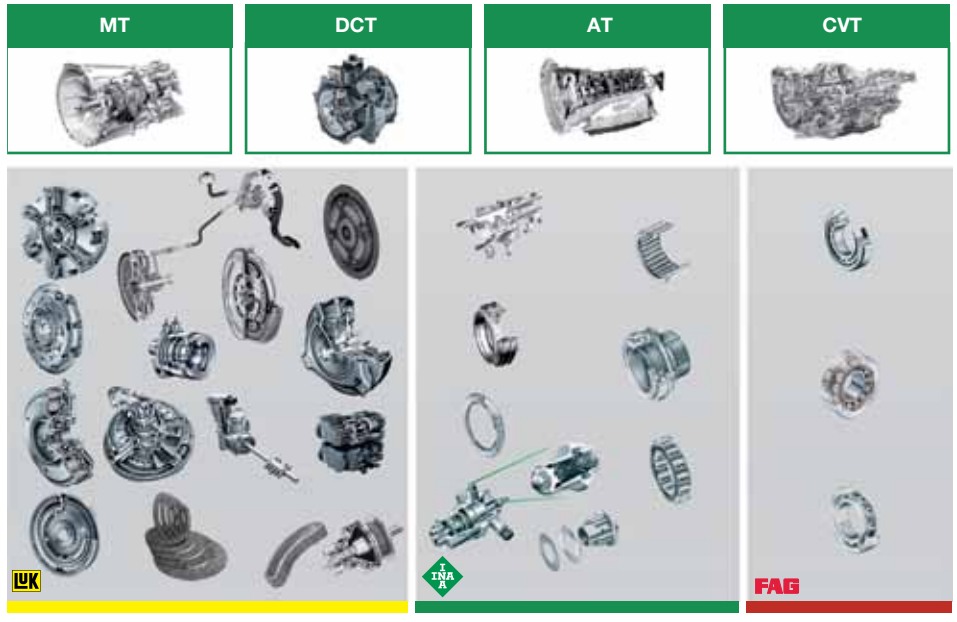

Figure 1 Samples from the product portfolio of the Schaeffler Group's Transmission Systems Business Division designed to reduce losses and optimize comfort as well as NVH behavior

Reducing consumption by means inside the transmission

An analysis of energy losses in the chain from well to wheel shows that the greatest percentage of energy losses occurs when the chemical energy bound up in fuel is converted to mechanical power at the crankshaft. This is due to the high thermodynamic and friction losses in the internal combustion engine.

In contrast, the power transmission efficiency is up to more than 90 %, depending on the transmission system and operating conditions. Nevertheless, efforts to reduce this rather low proportion of the losses are valuable as well, since such optimizing measures usually generate minimal additional costs relative to the increase in efficiency. Due to legislative regulations that – starting in 2020/2021 – will bring penalties of up to 95 euros per g/km in excess of a CO_2 emission limit of 95 g/km in the EU, clear target values can now be derived with regard to the additional expenditure that is acceptable in order to increase efficiency.

In presentations at the 10th Schaeffler Symposium in 2014, many solutions for reducing CO_2 emissions will be introduced in detail. Figure 1 provides an overview of the product portfolio.

In planetary automatic transmissions, plain bearing supports are being increasingly replaced by rolling bearing supports. Needle roller bearings are very frequently used for this application and in the case of planet gear bearing supports are subjected to centripetal acceleration. In the most recent nine-speed automatic transmissions, both for inline and FWD arrangements, values up to 7,200 *g* must be taken into consideration and made sustainable by means of a suitable design (Figure 2).

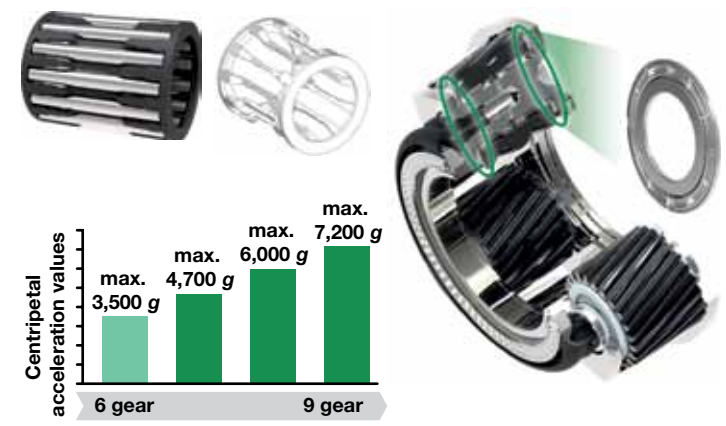

Figure 2 Centripetal acceleration values in the planet gear bearing supports of automatic transmissions and a newly developed axial needle roller bearing support for planet gears with a high relative speed

For the CVT, the advantages of the LuK chain with low-friction rocker joints compared to other CVT linking elements [2, 3] are being increasingly implemented on the market with an improved fuel consumption of up to 4 %. Starting with applications that have a high torque of 400 Nm, chains with smaller pitch lengths are now being used as well. Besides the volume-produced 08 and 07 chain types, the smaller 06 and 05 types are being developed in order to make use of the robustness and efficiency advantages in the lower torque and vehicle class range also.

Startup elements

A broad portfolio of startup elements is produced under the Schaeffler LuK brand – from a dry clutch for manual transmissions and torque converters to double clutch systems with a wet or dry design.

Hydrodynamic torque converters

Along with optimizing the hydrodynamic circuit in order to keep losses to a minimum even in open converter operation, the hydrodynamic torque converters provided for automatic transmissions take the following key developmental aspects into account:

- High-capacity torsional dampers, including centrifugal pendulum-type absorbers running in oil that facilitate early lock-up even at very low engine speeds and
- Reduction of the rotating masses being accelerated.

Great progress is being made with the new development referred to as iTC with its innovative integration of the lock-up clutch into the turbine wheel [4] (Figure 3).

Double clutch systems and their actuators

For double clutch system solutions [5, 6], which are gaining an ever greater share of the market, Schaeffler's LuK brand has been offering dry double clutch systems since the end of 2007. In contrast to wet double clutches, they have the advantage of not causing fluid-induced drag losses in the passive clutch, which account for approx. 2 % fuel consumption and CO_2 emission advantages in the NEDC. In the meantime, volume-produced dry double clutches have been delivered to five international OEMs and transmission manufacturers, even for hybridized versions (Figure 4).

The range of applications of dry double clutch systems currently includes engine torques of up to 250 Nm. The main objective of current development work is to continue optimizing comfort features in order to meet increasing demands and the wide range of usage profiles – including for hybridized powertrains.

After Schaeffler had already been involved in the initial basic development of wet multi-disk clutches in the 300 Nm range, volume production of the first wet double clutches from Schaeffler's LuK brand started in 2013 (Figure 4 right).

In many applications, LuK not only offers double clutches, but also the clutch actuation system with optimized auxiliary energy consumption. For example, the lever actuator made it possible to pursue the power-on-demand principle so that the clutch can be actuated with small electric BLCD motors and the electrical power consumption is under 20 W during practical driving operation including electromechanical gear actuation [7].

Moreover, volume production has begun for a new electrically operated hydrostatic clutch actuator (HCA). The HCA was developed in a modular design approach so that it could be used for actuating both dry and wet double clutches in conjunction with engagement bearings.

At the same time, volume production of a new kind of gearshift actuator was launched, which uses the active interlock concept to actuate all of the gears of the hybridized double clutch transmission with the help of two electric motors. This actuator was also developed with a modular design so that it can be used in both dry and wet double clutch transmissions (Figure 4 left and right).

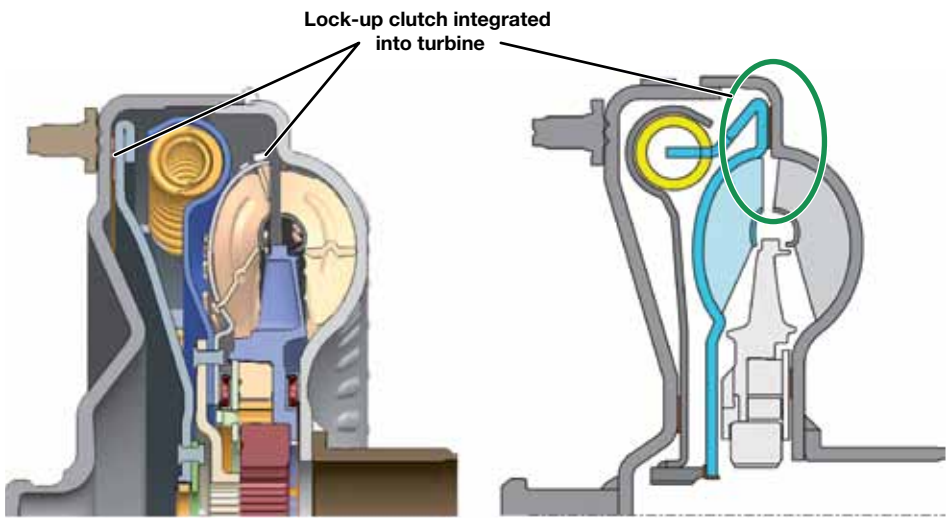

Figure 3 Innovative iTC with lock-up clutch integrated into the turbine wheel

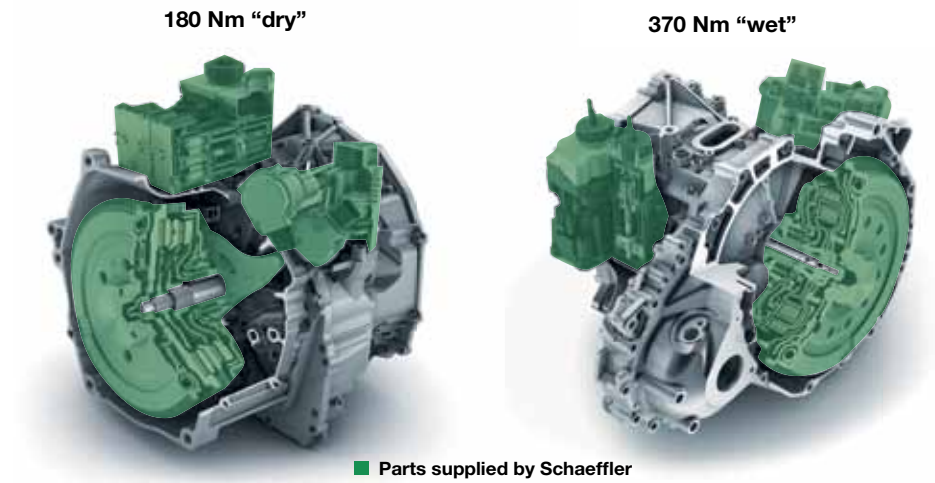

Figure 4 Dry and wet running double clutch systems, including electrically power on demand operated clutch and transmission actuators from Schaeffler for hybrid transmissions

Damper systems for torsional vibration isolation

Trends in engine development place high requirements on damper systems:

- Downsizing to reduce internal engine losses resulting in higher torsional vibration excitation due to lower numbers of cylinders coupled with lower excitation frequencies
- Higher turbocharging pressures with a corresponding torque increase and higher peak pressures, leading to increased excitation amplitudes
- Downspeeding with high torques even at very low engine speeds thanks to optimized turbocharging concepts, which leads to even lower excitation frequencies coupled with very high amplitudes.

The developmental history of damper systems extends from the transition from torsionally damped clutch disks to the dual mass flywheel with an extremely low first natural frequency and corresponding isolation of all higher excitation frequencies to the introduction of the centrifugal pendulum-type absorber (Figure 5).

The centrifugal pendulum-type absorber is a kind of vibration absorber, whose frequency is inherently regulated by the engine speed frequency due to the centrifugal effect so that the damping effect can be utilized for all speeds according to the main engine vibration order. Due to the positioning of the centrifugal pendulum-type absorber (CPA) on the secondary side of the dual mass flywheel (DMF), it was possible with a small mass to achieve a significant additional reduction of the engine excitation on the transmission input shaft, which was already insulated by the DMF. This is used for both manual transmissions (MT) and double clutch transmissions (DCT). It has not been needed in previous applications of dry double clutch transmissions, since the required thermal masses of the pressure plates already provide sufficient isolation for torsional vibrations with conventional dual mass flywheels. It has been possible to use the centrifugal pendulum-type absorber even in torque converter dampers (Figure 6).

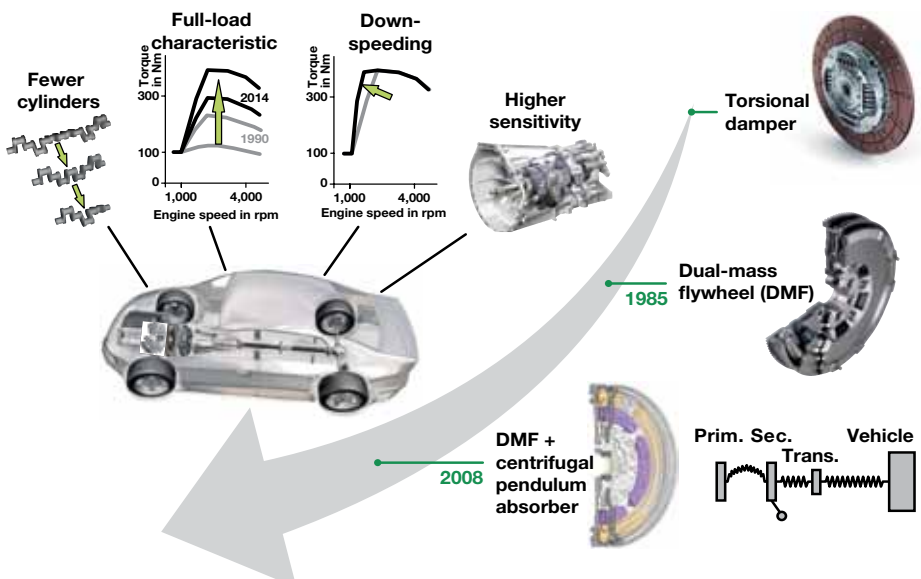

Figure 5 History of damping system development

When used in torque converters, it is important to consider here that the centrifugal pendulum-type absorber is immersed in oil, meaning that corresponding adjustments of the characteristic curve must be calculated by means of simulations and measurements on the component test stand and in the vehicle in order to arrive at optimum operational results. By using the centrifugal pendulum-type absorber, it is possible to close the lock-up clutch sooner, for one thing – at speeds even below 1,000 rpm – and, for another, to avoid loss-inducing acoustic micro-slip. Besides saving on consumption, this also achieves a stronger connection in the entire powertrain with a better dynamic sensation.

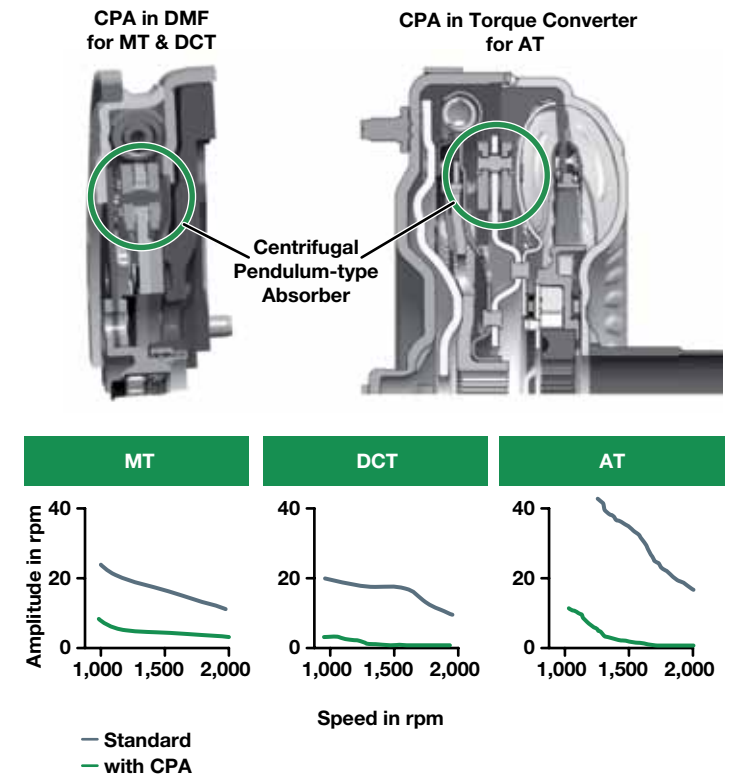

Figure 6 Use and effect of the centrifugal pendulum-type absorber in dual mass flywheels for manual and double clutch transmissions as well as in torque converters

Damper systems for cylinder deactivation

The deactivation of cylinders in internal combustion engines running under partial load is increasingly being introduced for reducing fuel consumption and CO_2 emissions. This leads to the requirement for the damper system to ensure good NVH quality when the engine is operating both on all cylinders and a partial number of cylinders. The easiest solution is still to manage a V8 engine running on four-cylinders. Depending on the application, a conventional damper can be designed for when the engine is operating on all cylinders and the additional centrifugal pendulum-type absorber designed for cylinder deactivation operation only so that good torsional vibration behavior can be ensured in both cases. In a four-cylinder engine with the

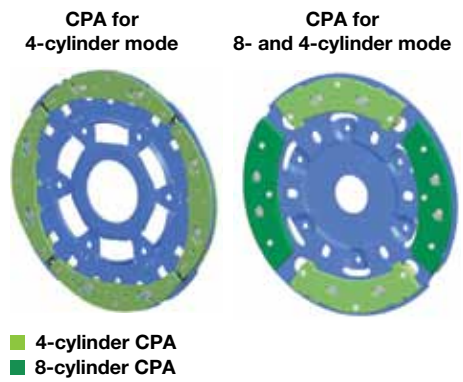

Figure 7 Centrifugal pendulum-type absorber combination matched for operation of the engine on all cylinders and with cylinder deactivation

two center cylinders deactivated, it has been sufficient to implement an adequate damper solution by optimizing a two-stage curve for the dual mass flywheel due to the limited torque range in two-cylinder operation.

However, new applications with very high nominal torques, both in V8 and four-cylinder engines are resulting in increased requirements, both when operating the engine on all cylinders and a partial number of cylinders. Solutions are being developed that actually incorporate two different centrifugal pendulum-type absorber systems in order to optimize both operating modes independently of each other (Figure 7). To do so, one pair of pendulum-type absorbers is calibrated for operation of the engine on all cylinders and the other for operation on a partial number of cylinders with half of the primary order of excitation.

New kinds of rolling cylinder deactivation for the "1.5-cylinder engine"

If additional CO_2 reduction must be achieved by means of cylinder deactivation for three-cylinder engines as well, this raises the question as to whether this can be attained through simple static cylinder deactivation. Torsional vibration simulations indicate large excitation amplitudes, however (Figure 8).

What is more, the order analysis shows that excitation is mainly characterized by a very low 0.5th fundamental order (Figure 9). This can hardly be brought to a torsional vibration level that is acceptable for the powertrain with the damper designs of today.

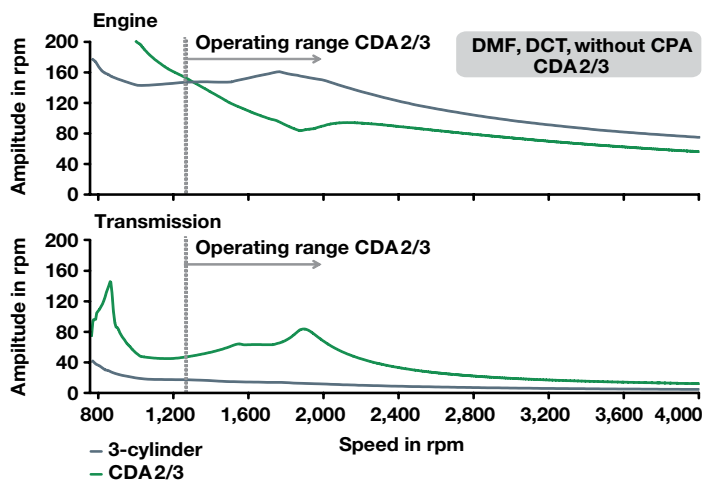

Figure 8 Torsional vibration excitation for conventional static cylinder deactivation with two of the three cylinders active (CDA 2/3)

Further reflections on the physical and mathematical background of the origin of excitation orders have led to the suggestion of designing rolling cylinder deactivation in three-cylinder engines, ultimately leading to "1.5-cylinder operation" (Figure 10). The basic idea is that the time signal of excitation recurs already after two cylinder operating cycles have elapsed if there is alternation between the active and inactive cylinder. The frequency spectrum of excitation is therefore determined by a fundamental frequency resulting from the inverse of the duration of only two consecutive cylinder operating cycles, and their higher harmonics. The periodic recurrence comes after just 2/3 of a camshaft revolution and not only after a complete revolution, as would be the case with static deactivation of a fixed cylinder.

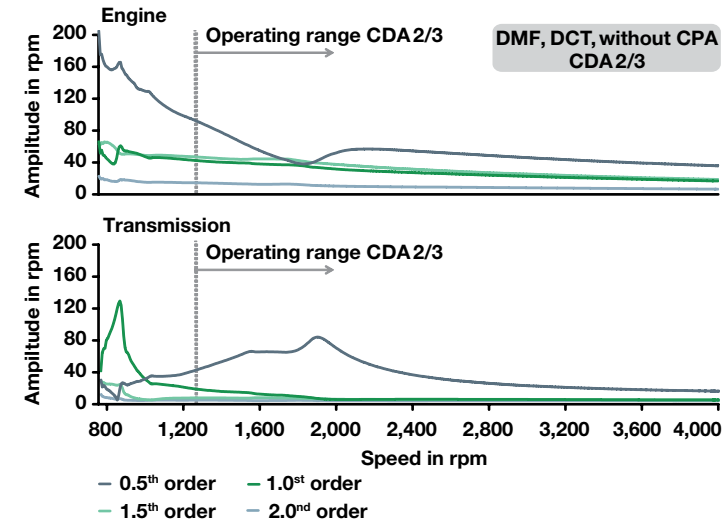

Figure 9 Order analysis with conventional static cylinder deactivation CDA 2/3

The fundamental frequency of the excitation function is 3/2, or 1.5 times the cam-

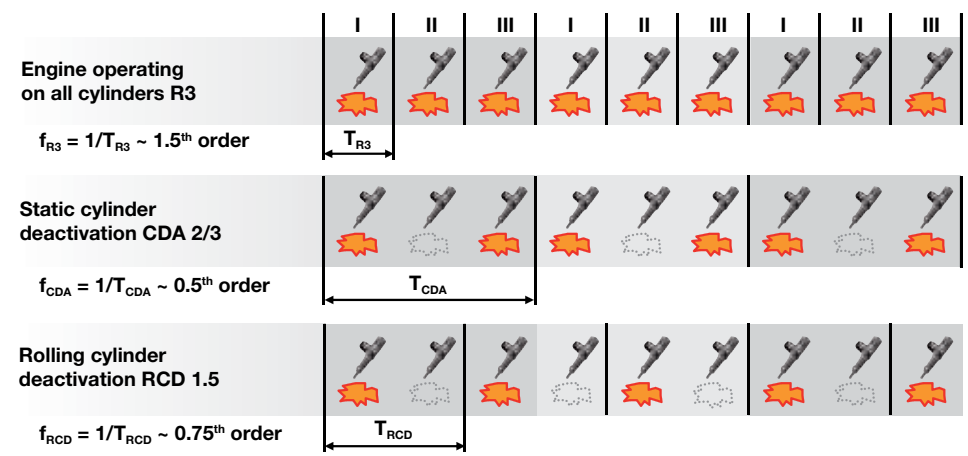

Figure 10 Principle of rolling cylinder deactivation "RCD 1.5" with 1.5 of the three cylinders active

shaft speed and thus the 0.75th order of the crankshaft frequency (Figure 11). It is plausible that the alternating operation of active and inactive cylinders in three-cylinder engines results in 1.5-cylinder operation, generating a 0.75th fundamental order for the four-stroke cycle principle.

The rolling cylinder deactivation "RCD 1.5" suggested here with 1.5 rolling active cylinders out of three cylinders therefore offers the following basic advantages over static cylinder deactivation with two fixed active cylinders out of three cylinders (CDA 2/3):

- Fundamental excitation frequency of the 0.75th order instead of the practically uncontrollable low-frequency 0.5th order, with all excitation frequencies 50 % higher – the main objective of this development;
- Even higher reduction in fuel consumption due to only 1.5 instead of two active cylinders.

As a result of further tests, it is possible to provide the following advantages over static cylinder deactivation as well:

- No oil suction due to a vacuum, since each deactivated cylinder is actively fired during the next camshaft revolution, and thus there are no prolonged vacuum phases in the cylinder.
- This also prevents the deactivated cylinder from cooling down, thereby reducing heat-related cylinder distortion during deactivation operation.

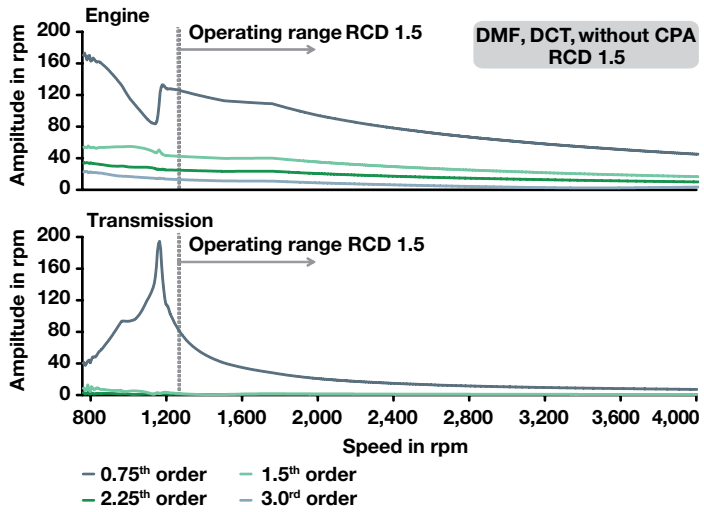

Figure 11 Order analysis for RCD 1.5 operation with a 0.75th fundamental order without centrifugal pendulum-type absorbers

- Since no cylinders are deactivated for prolonged periods with the RCD 1.5 concept, fewer warmup measures are needed than for the static cylinder deactivation concept. For this reason, it is possible to drive in RCD 1.5 mode even directly after a cold start, which leads to another improvement in fuel consumption compared to static cylinder deactivation.

Optimizing cylinder charging in deactivation operation

At this point, one might ask how and with what charges the deactivated cylinders should be operated. With current cylinder deactivation systems, fresh air is generally locked into the deactivated cylinder, where it is compressed and passively expanded without combustion. In principle, the options of "exhaust gas in the cylinder" or "nearly no gas in the cylinder" are also open for discussion. A deactivated cylinder compresses and expands twice without ignition and combustion during one revolution of the camshaft, while an active cylinder in four-stroke operation only compresses and expands once, using the second half of the camshaft's revolution to exchange the gas. Excitation therefore originates from a deactivated cylinder twice per camshaft revolution and only once from an active cylinder.

Consideration of the three options for potential cylinder charging leads to the following results for RCD 1.5:

- Variant 1, leaving the exhaust in the cylinder:
  Here, relatively high working pressures occur analogous to the pressure of the residual gas, which is unfavorable with respect to thermodynamic process and friction losses. Moreover, the torsional vibration excitation in the 0.75th order is unacceptable due to the high exciting cylinder pressures.
- Variant 2, fresh air in the cylinder:
  The disadvantage here are the losses due to working pressures. In addition, excitation still partly produces the 0.75th fundamental order here due to the additional second "dummy" compression in asynchronous phasing relative to the omitted ignition.
- Variant 3, almost no gas in the cylinder:
  After expelling the last combustion gas from the previous stroke, the intake and exhaust valves remain closed so that the piston completes two intake strokes against a vacuum, after which compression occurs with a large portion of the compression energy being recuperated. The second time that the piston returns to TDC, the intake valves are then reopened so that the normal intake, compression, ignition, and exhaust operation is restored.

Simulations of torsional vibration excitation based on the cylinder pressure curves do not indicate the presence of any dis-

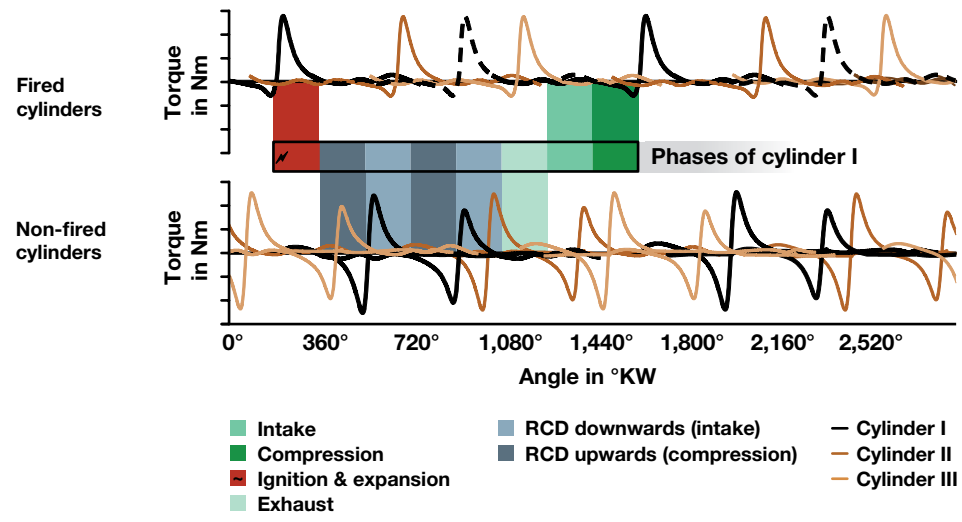

Figure 12 Formation of alternating torques of cylinder deactivation operation in three-cylinder engines in the variant with relatively high exhaust gas pressure in the cylinder

turbing low-frequency 0.5th order; instead, the lowest occurring order is the 0.75th, as expected. The excitation amplitude is smaller than with the first two cylinder charge options and basically stems from the lack of ignition and to a lesser degree from the dummy intake strokes completed against a vacuum with subsequent recompression. Advantageous here is the fact that relatively low pressures are involved, so that the friction losses in the deactivated cylinders are small, thereby achieving a considerable reduction in fuel consumption. Since the deactivated cylinder is fired normally on the next camshaft revolution, no oil is sucked in despite the short vacuum phase.

Implementing the RCD concept with various numbers of cylinders

The outcome that must be kept firmly in mind is that the RCD 1.5 concept in conjunction with nearly no cylinder charge attained the best results with respect to both a reduction in fuel consumption as well as torsional vibration excitation. In essence, 1.5-cylinder operation was realized with a three-cylinder engine. The cycles of the individual strokes and the RCD strokes contained in them are portrayed in Figure 13.

Using the same principles, a five-cylinder engine can effectively be operated as a 2.5-cylinder engine with RCD 2.5 in cylinder deactivation operation. Fundamental excitation then occurs in a 1.25th order, which can be controlled by means of relevant damper systems.

Rolling cylinder deactivation can also be implemented in engines with an even number of cylinders. For example, depending on the power required, a four-cylinder engine can either run as RCD 1.33 or as RCD 2.66 along with normal static deactivation CDA 2/4. A 0.66th fundamental order is produced, however, in the first two cases that is hard to control due to the fundamental period duration according to the sequence of three of the four cylinders up to the periodic recurrence of the sequence.

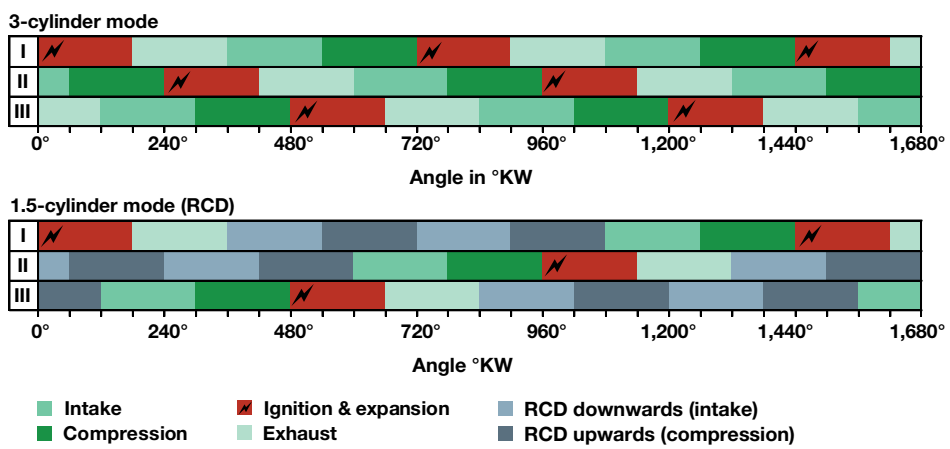

Figure 13 Comparison of the stroke cycles in a three-cylinder engine operating on all cylinders and in RCD 1.5 operation

The valve control required for RCD operation, i.e. the deactivation of intake and exhaust valves of each cylinder being deactivated during a camshaft revolution, can be implemented so as to be completely variable with the Schaeffler UniAir system for electro-hydraulic valve actuation [8].

As a rule, the intake and exhaust valves can be deactivated by means of switching mechanisms as well [9]. Options include switchable tappets, finger followers, pivot elements, and – with certain limitations – even the principle of cam shifting. These types of components are currently used for valve switching, and are capable of switching within parts of a camshaft revolution. In order to be used with RCD 1.5 and the considerably greater number of switching cycles involved, further development would be required, since switching would have to occur after each camshaft revolution.

Torsional vibration damper development for RCD 1.5

The 0.75th fundamental order occurring in RCD 1.5 operation places heavy demands on the torsional damper system. Figure 14 shows a design solution in connection with dry double clutches – the result of DMF optimizations and a centrifugal pendulum-type absorber designed for the 0.75th order. Due to the advantage of the overall length of three-cylinder engines as compared to four-cylinder engines in identical vehicles, it was possible here to choose a design for which the arc spring damper and the centrifugal pendulum-type absorber masses are both arranged axially one behind the other on large effective radii.

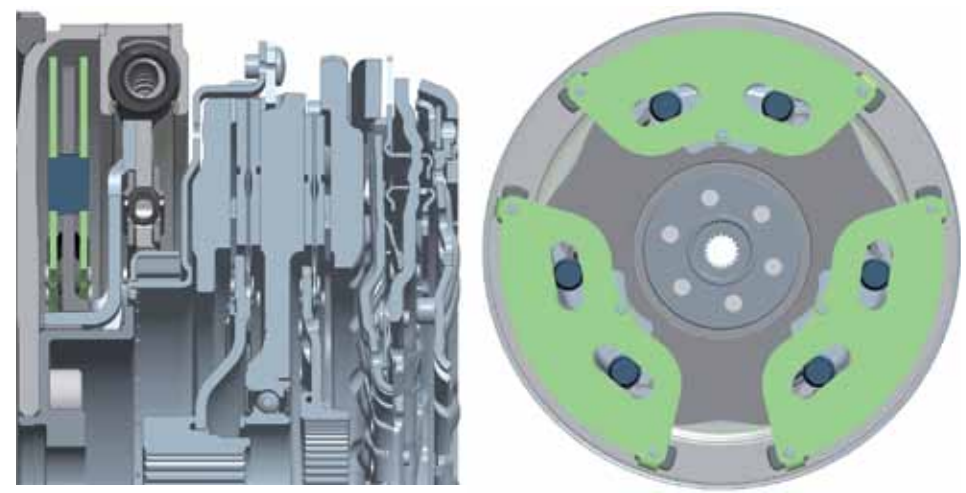

Figure 14 DMF design with a centrifugal pendulum-type absorber for the 0.75th order for RCD 1.5 rolling cylinder deactivation in three-cylinder engines

The resulting order analysis of the simulations shows how the excited 0.75th order is reduced by the matched centrifugal pendulum-type absorber to the very low amplitudes on the transmission input (Figure 15).

Figure 16 depicts the behavioral comparison of a three-cylinder engine running operating on all cylinders and under full load as well as in cylinder deactivation operation according to the RCD 1.5 principle at its highest operating load, which is set at 70 % of the theoretically highest producible half-engine torque. It is evident that practically the same speed amplitude occurs under such conditions at the transmission input in RCD 1.5 operation as when the engine is operating on all cylinders. The means for this is the centrifugal pendulum-type absorber with a total mass of approx. 1 kg that has been optimally matched for the occurring 0.75th order.

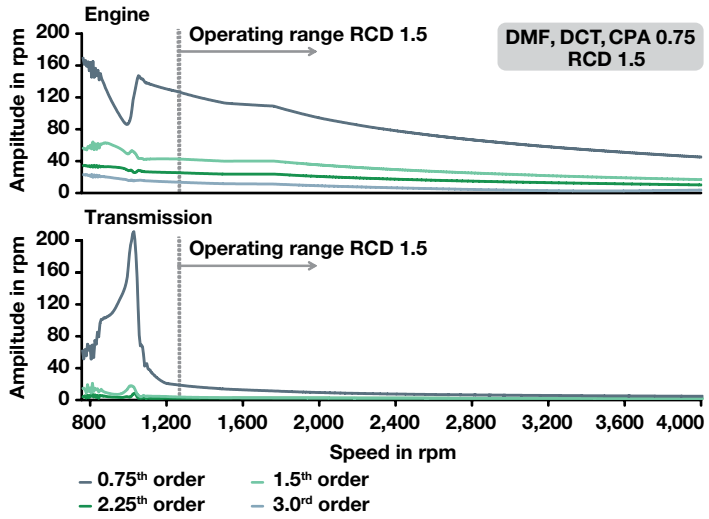

Figure 15 Order analysis of RCD 1.5 operation with a centrifugal pendulum-type absorber

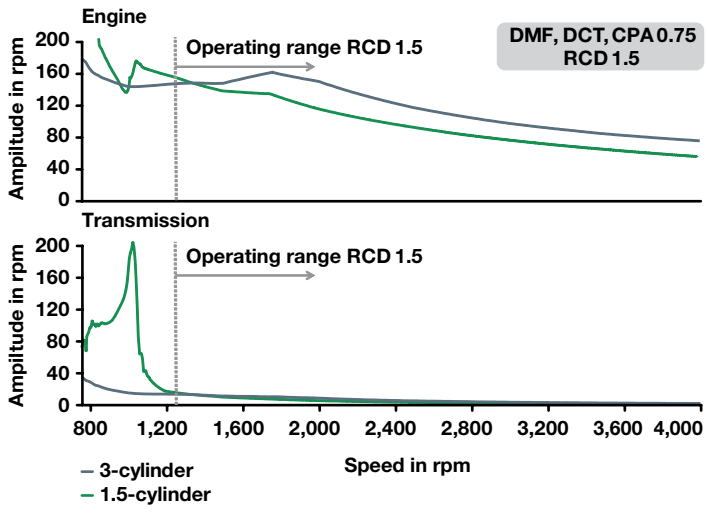

Figure 16 Comparison of torsional vibrations in the powertrain in a three-cylinder engine operating on all cylinders and for rolling cylinder deactivation in RCD 1.5 operation with a dry double clutch

In addition, a centrifugal pendulum-type absorber approx. 800 g larger was designed for manual transmissions for which the secondary moment of inertia of the mass is less than with the dry double clutch, which has a thermal mass that is practically used twice (Figure 17).

In this way, the goal of implementing cylinder deactivation operation in three-cylinder engines with acceptable torsional vibration behavior in the powertrain was achieved, both with a dry double clutch and for manual transmissions. In RCD 1.5 operation, this can in effect be managed with only 1.5 active cylinders to reduce fuel consumption and CO_2 emissions.

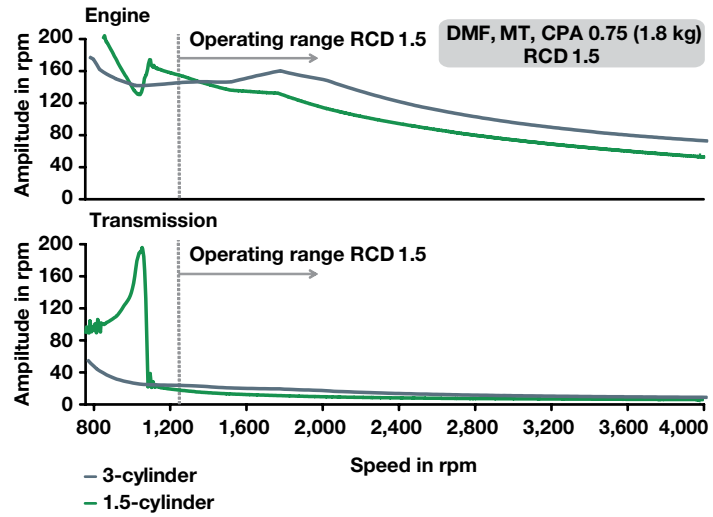

Figure 17 Comparison of torsional vibrations in the powertrain in a three-cylinder engine operating on all cylinders and for rolling cylinder deactivation in RCD 1.5 operation with a single clutch for manual transmissions with a larger centrifugal pendulum-type absorber

Summary

This article describes measures for reducing fuel consumption and CO_2 emissions in motor vehicles to the extent that they are primarily influenced by transmission systems:

- Direct friction reduction in the transmission through optimized bearing supports
- Wet and dry double clutches with reduced drag torque
- Transmission designs with a large spread of gear ratios
- Optimized damper technology for achieving downsizing and high turbocharging pressures, along with downspeeding for reducing losses in combustion engines.

Such drive trends are related to an increase in torsional vibration excitation from the internal combustion engine into the powertrain. Finally, a new approach is introduced for implementing RCD 1.5 rolling cylinder deactivation for three-cylinder engines to attain 1.5-cylinder operation. The basic characteristics are:

- Sophisticated rolling cylinder deactivation in order to increase the fundamental frequency of the excitation spectrum from the 0.5th order with static cylinder deactivation to the much more controllable 0.75th order with rolling cylinder deactivation
- Optimized cylinder charge setting to reduce the excitation amplitude.

The resulting torsional vibration excitation is controlled by the innovative damper technology developed by Schaeffler, which entails a dual mass flywheel with an optimized curve, the use of centrifugal pendulum-type absorbers on the secondary DMF mass that are matched to the occurring 0.75th main excitation order, and an additional damped clutch disk if needed. Similarly, it is possible

to implement RCD 2.5 operation, which is advantageous for five-cylinder engines.

This approach can be implemented for applications with manual transmissions (MT), automated manual transmissions (AMT), double clutch transmissions (DCT) with a dry or wet double clutch, and also for planetary automatic transmissions or CVTs with converters that have dampers equipped with added centrifugal pendulum-type absorbers.

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