Dual Mass Flywheel

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Introduction

The first mass-produced dual mass flywheel (DMFW) in automotive history went into production around 1985. A brief historical review (Figure 1) shows the development of the DMFW. In the beginning, unlubricated dampers were used, which had heavy springs located far to the outside that exhibited wear problems. Around 1987, the first grease-lubricated DMFWs were used and service life was no longer an issue.

The introduction of the arc spring damper was a breakthrough for the DMFW in 1989 that solved almost all of the DMFW resonance problems at once. In addition, costs were continually reduced [1-4].Initially, the primary flywheel mass was a casting or forged steel. Later, the metal-forming specialists at LuK were successful in forming all of the parts except for the secondary flywheel mass from formed sheet metal parts. To increase the primary mass moment of inertia, folded masses were developed from sheet metal (1995). This formed the basis for broad usage of the DMFW. This intensive detail work paid off with a large increase in DMFW production (Figure 2).

With an estimated production volume of approximately 2 million DMFWs for 1998, the noise and comfort behaviour of every fifth car with manual transmission in Europe will be improved by the DMFW. Figure 3 illustrates the allocation according to engine displacement and gasoline / diesel engine class. It is apparent that engines with more than 2.0 liter engine displacement, particularly gasoline engines, are predominantly equipped with DMFW. The use of DMFW for mid-size engines only began a few years ago. There are currently only a few projects for engine displacement less than 1.6 liter.

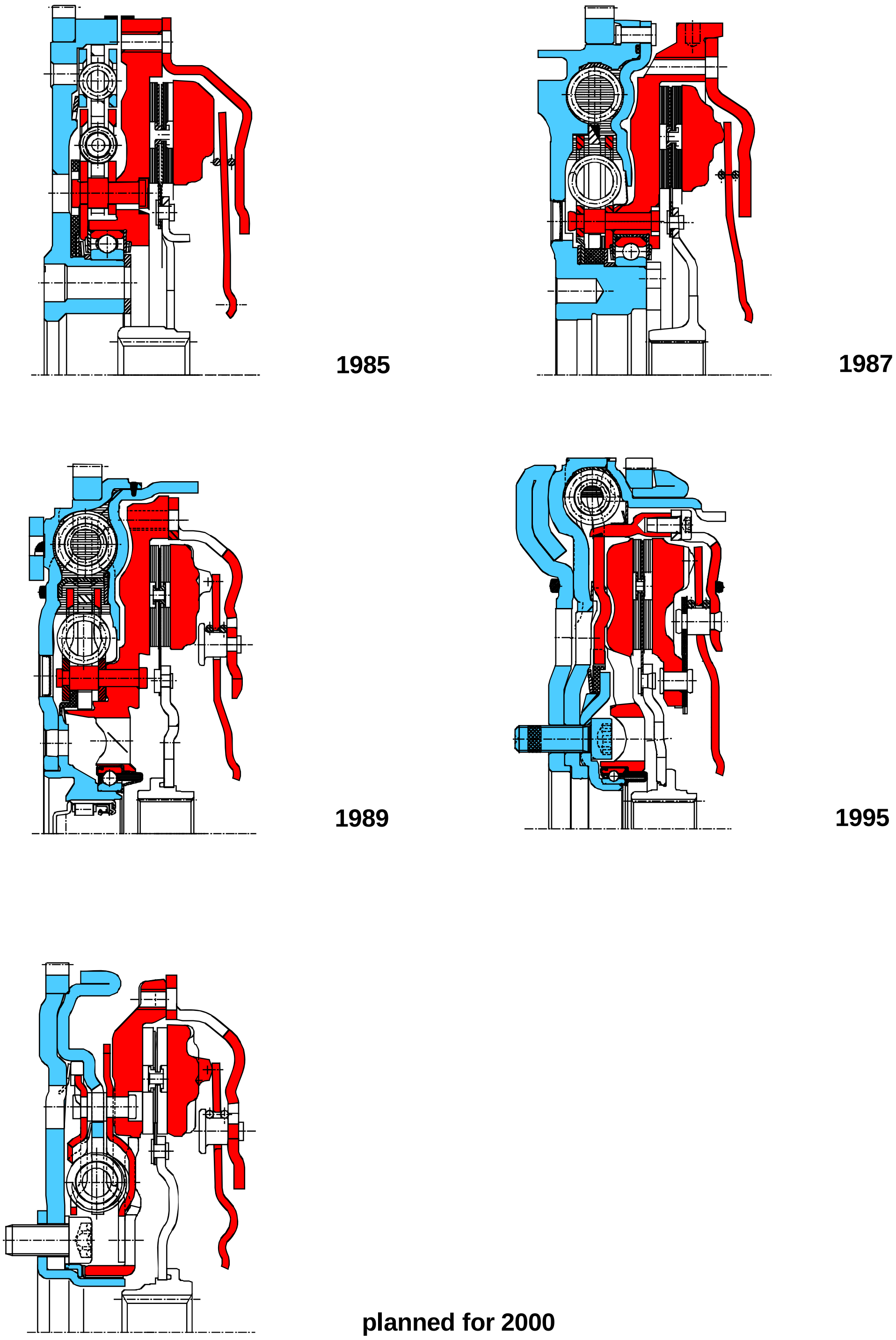

Figure 1: Development history of the DMFW

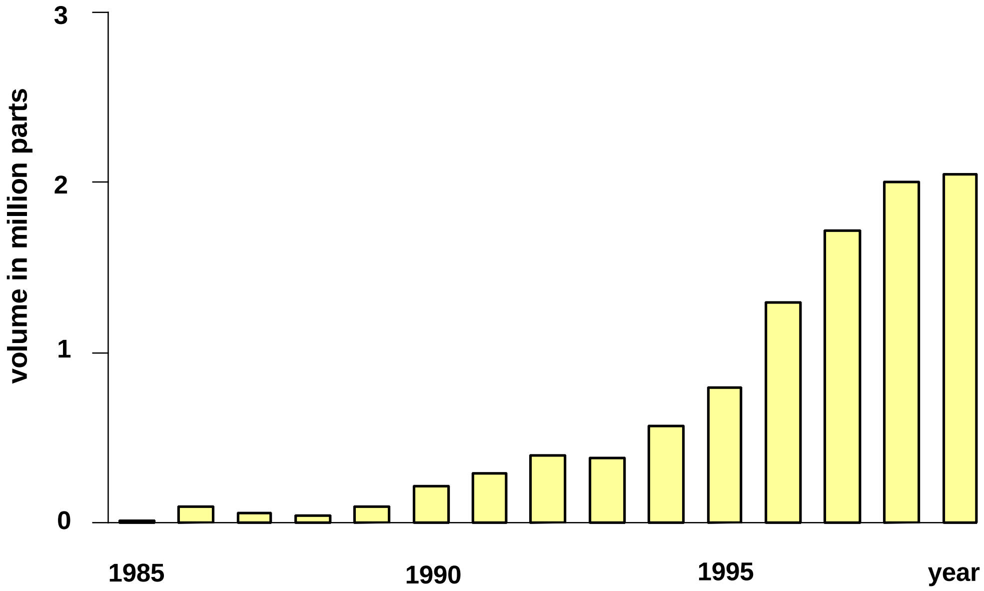

Figure 2: Development of DMFW production for German car manufacturers

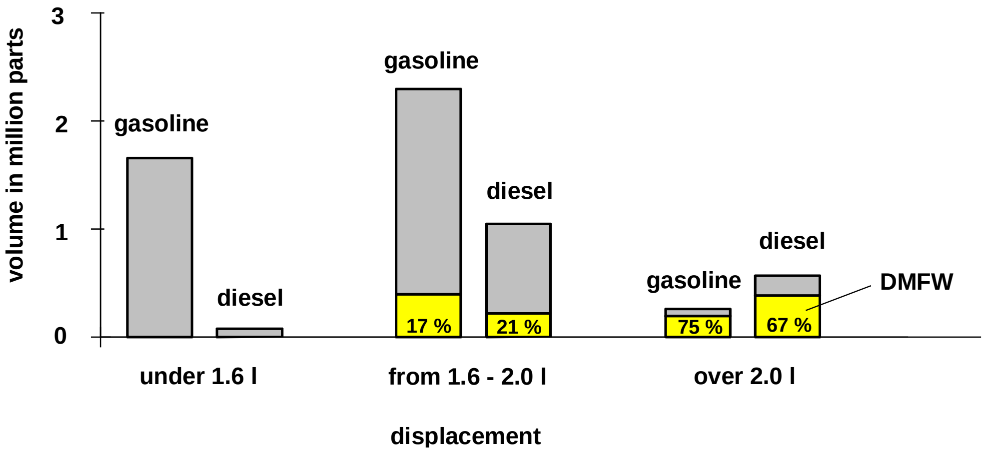

Figure 3: Portion of vehicles with DMFW for different engine classes (1997)

LuK expects that in a few years the saturation will be similar for at least mid-size engines as it is today for powerful engines because a DMFW shows its advantages in all vehicles. It has not been used thus far in smaller cars due to its high costs.

Hence, a critical point in the development of DMFW is reducing costs. A later part of this presentation will cover this issue.

Advantages of the DMFW

Although not everyone wants the DMFW due to the costs, the achievable improvements are so clear that it is being used extensively in large vehicles. The most important advantages will be outlined below.

Isolation from Torsional Vibrations

The primary feature of the DMFW is the almost complete isolation of torsional vibrations. This has been discussed extensively in earlier presentations and will only be summarized here.

Figure 4 illustrates the angle accelerations at the transmission input for a conventional system with a torsion damper in the clutch disc (left) in comparison to a DMFW (right). With the torsion damper in the clutch disc, there is no significant vibration isolation achieved at low speeds. Resonance can be avoided by selecting appropriate damping.

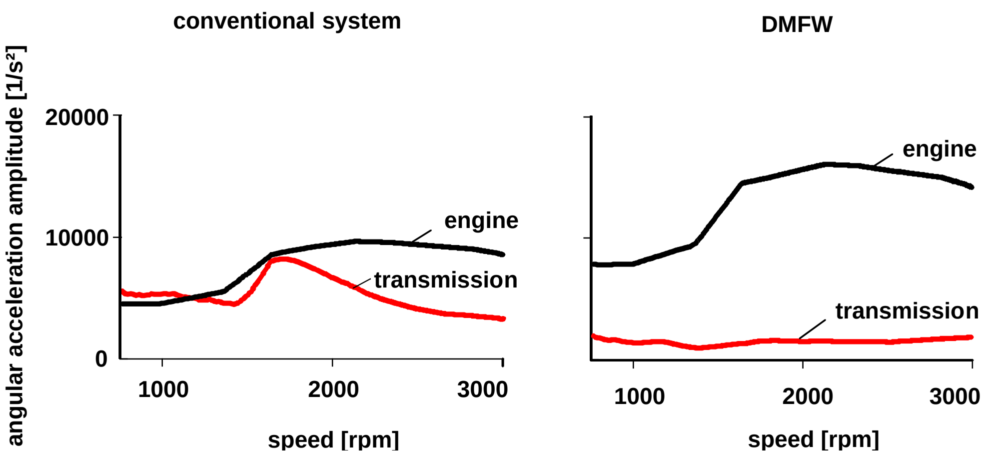

Figure 4: Comparison of vibration isolation of a conventional system to a dual mass flywheel

In contrast, the DMFW almost completely filters out the engine irregularity. Resonance generally no longer occurs in the driving range. Gear rattle no longer occurs due to the almost uniform operation of the secondary flywheel side and thus also of the transmission input shaft. Annoying droning can also be almost completely eliminated.

The irregularity of the engine itself becomes greater with DMFW because the primary flywheel mass is lower than the conventional flywheel mass with a clutch. Therefore, the accessory drive must occasionally be retuned. The smaller primary flywheel mass also has advantages, as will be presented later.

Good vibration isolation, particularly during low-speed driving, often leads to low-consumption operation, which saves fuel due to the predominantly low engine speeds used. Many modern engines with a relatively flat torque curve favor this consumption-reducing operation.

Transmission Relief

Another positive effect results from the transmission relief. The drive train and hence also the transmission are relieved of stress due to the elimination of engine irregularities.

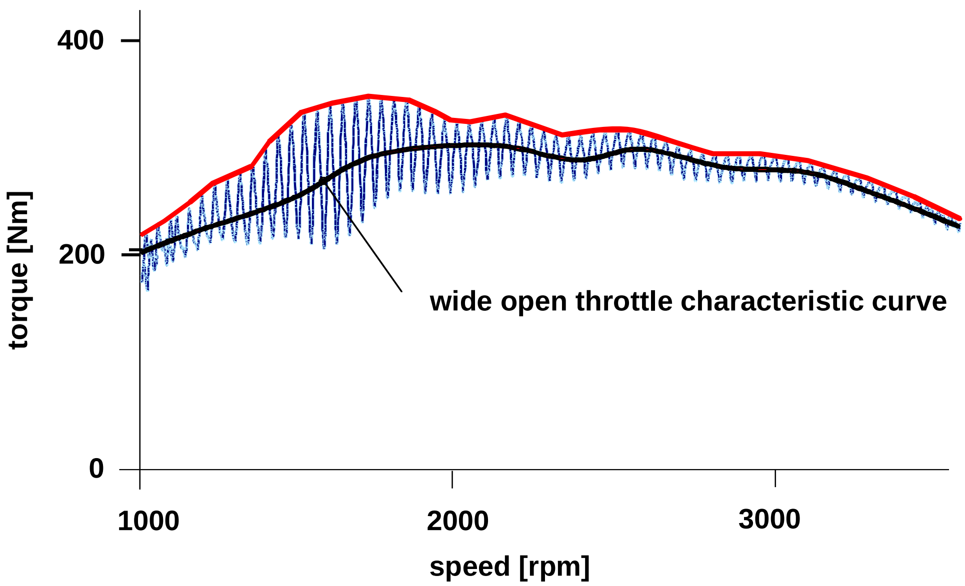

Figure 5: Increase of the actual effective torque in the transmission due to the engine irregularity

Figure 5 illustrates the wide open throttle characteristic curve of a typical diesel engine. For a conventional drive train, the additional dynamic torques as a result of the irregularity are superimposed. Depending on the speed, they can generate more than 10 % additional load.

The DMFW almost completely eliminates the additional high-frequency torques. Since the transmission is relieved, a higher static torque can be transferred, particularly with diesel engines with DMFW (figure 6).

	gasoline	**diesel**
conventional	**100 %**	**100 %**
DMFW	**105 %**	**110 %**

Figure 6: Increase of the transmission load capacity when using a DMFW. The load capacity for the conventional drive train is assumed as 100 % for both gasoline and diesel vehicles.

Crankshaft Relief

The DMFW permanently alters the vibration system of the crankshaft. In the conventional system, the heavy flywheel including the clutch is rigidly connected with the crankshaft. The large inertia of the flywheel generates high reaction forces on the crankshaft.

The DMFW system behaves more favorably because the secondary flywheel mass can be disregarded for the bending load. It is only very loosely connected via the torsion damper as well as via the roller bearing to the primary flywheel mass and therefore generates practically no reactions.

The primary flywheel mass is much lighter than a conventional flywheel and is also elastic, like a flexplate for a torque converter.

Inherent bending and torsion resonance forms change with the DMFW in comparison to a conventional system. The crankshaft is mostly relieved.

Figure 7 illustrates a measured example. Both torsion and bending vibrations are lower with the DMFW. In individual instances, it must be decided whether the crankshaft damper can be omitted or if a simpler material can be used for the crankshaft, such as a casting.

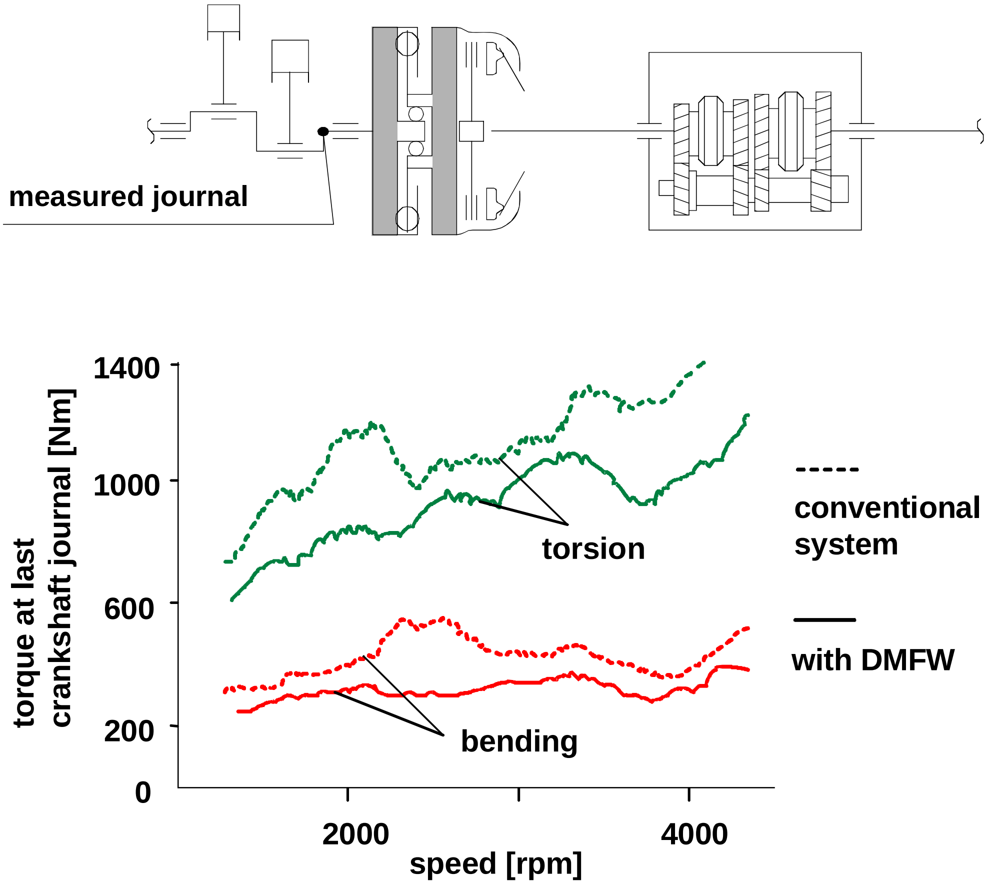

Figure 7: Reduction of the torsion and bending vibrations in the crankshaft using DMFW

LuK recommends that these opportunities for optimization be used in further vehicle developments. This could generate considerable savings. LuK is convinced that there are no additional costs from the DMFW if the secondary effects are taken into consideration.

Warranty

One of these secondary effects is the warranty. The DMFW was designed in the beginning to last the entire life of the engine. The replacement parts deliveries for the DMFW are actually few. Hence, the DMFW is a fully developed component for automotive drive trains.

Figure 8a illustrates the field complaints for a vehicle with a conventional drive train. Apparent is the disproportionately high number of complaints in the clutch area for which the clutch is not the actual cause. This is attributed to the fact that frequently, clutch discs are replaced along with the entire clutch because the customer complains about transmission rattle. Hence, the garage, which has no solution, replaces the entire system to pacify the customer. Generally, the replacement was not successful. Therefore, clutch discs were sometimes changed multiple times. Since not only the costs for the replaced parts, but also the numerous high disassembly costs were often covered at the company’s expense, there were exorbitant warranty costs, which transferred to the total production and partially added to the costs for the new clutch parts.

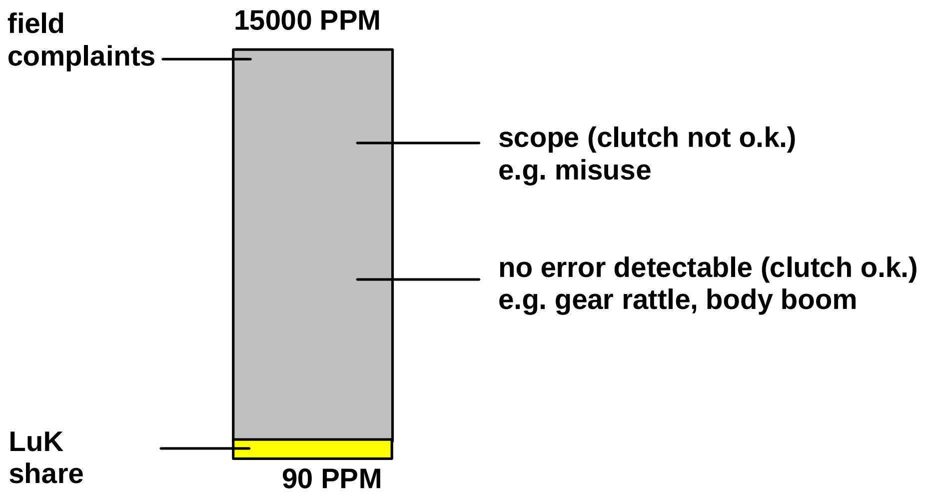

Figure 8a: Field complaints for a vehicle with a conventional drive train

The DMFW has put an end to this custom (Figure 8b). The complaints of this type have dropped so significantly that attention can finally be given to the actual cases of damage. Likewise, on site studies can be conducted instead.

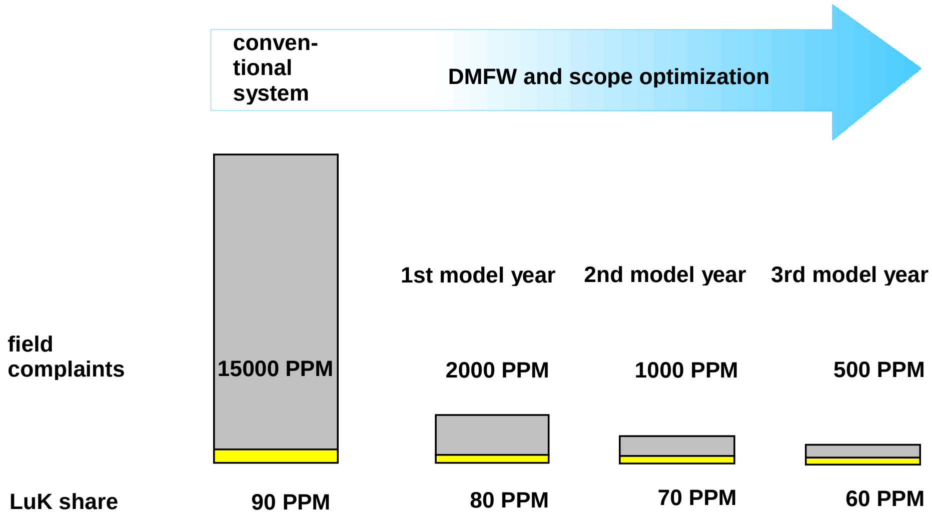

Figure 8b: Improvement in field complaints after using a DMFW

A few manufacturers are already considering this cost effect in the economic calculation if the issue is whether or not a DMFW should be used.

The DMFW is a mature product, but there is still further development potential.

Two aspects shall be discussed below.

Engine Start

The problem of resonance breakthrough when starting the engine was a primary issue from the very beginning of DMFW development. The good vibration isolation of the DMFW during driving operations was achieved in that the resonance frequency was shifted into the range below idle speed by the large secondary flywheel mass.

With each start of the engine, however, it must pass through the resonance frequency. This can lead to torques that are too high due to large inertias. The development of the DMFW was therefore characterized by a constant battle against resonance amplitudes.

It is known that resonance amplitudes are greater the higher the excitation from the engine. Hence, diesel engines with only four or even three cylinders place the highest demands on a DMFW. Every type of damping, such as basic friction, load friction devices, and arc spring friction has a favorable effect. Since these damping factors can diminish the isolation in varying degrees, naturally there are limits.

We have, however, received significant assistance because many newer, electronically controlled engines have an improved starting behaviour. The starting torque of the engine has turned out to be a determining factor that is significant for the formation of resonance. That is the torque with which the engine accelerates from the starter speed. The faster the resonance speed is passed through, the less the inertias can begin to vibrate.

Figure 9 illustrates simulations of a poor starting behaviour as speed over time.

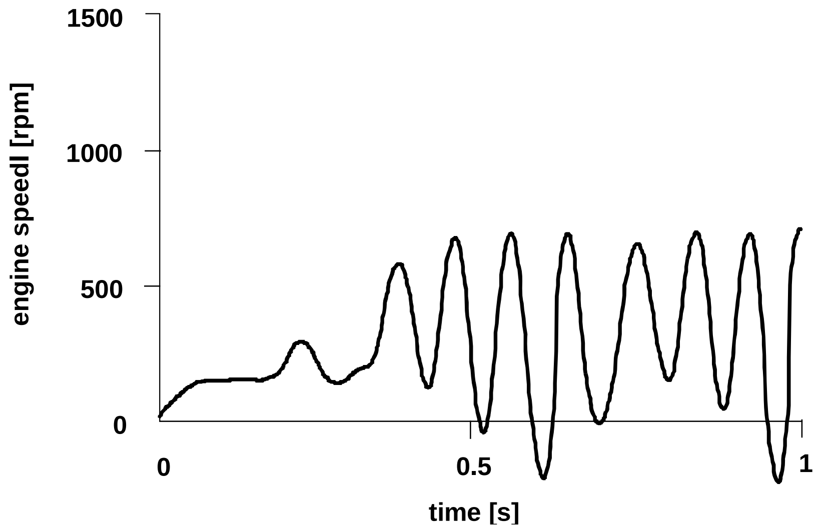

Figure 9: Poor starting behaviour (suspended start)

The cases (as in Figure 9) in which the engine remained in the resonance for a longer period of time or that did not even rev up on their own power are all critical. This is always the case if the engine power at starting rpm is so low that the entire energy is sapped by the highly vibrating system and there is no energy left over for revving up. This condition is also designated as suspended start and must absolutely be avoided with the DMFW because the long-lasting high amplitudes can cause mechanical damage to the components.

Figure 10a illustrates several start simulation calculations compiled in a matrix. The starting torque increases toward the top and the torque amplitude increases toward the right.

The matrix clearly shows how the engine starts well at higher starting torques and even manages for highly irregular engines.

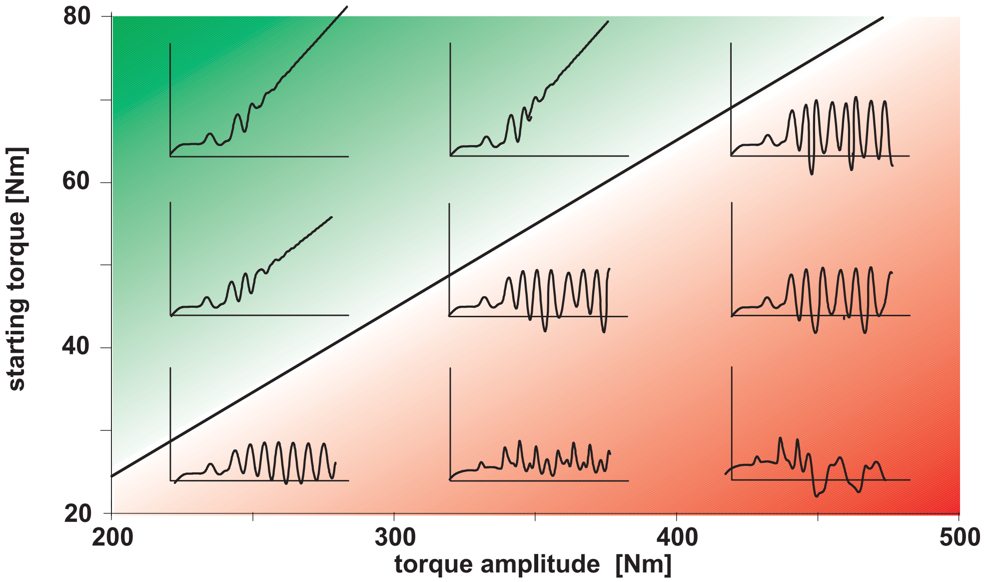

Figure 10a: Influence of torque amplitude (irregularity) and starting torque on the starting behaviour

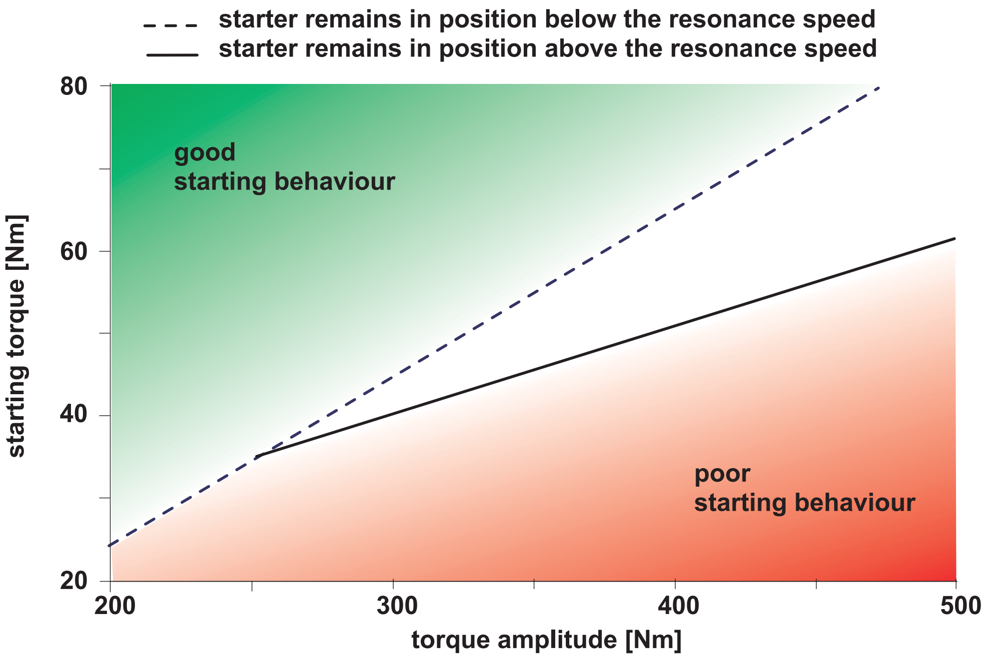

Figure 10b: Border lines for a good (upper left) and a poor (lower right) starting behaviour

Between this good starting behaviour and an unacceptable starting behaviour, there is a diagonal separation line, which is repeated again in Figure 10b. The range that is safe for starting lies above the separation line.

If the starter remains in position above the resonance speed, then the starter is prevented from immediately going out of position again by briefly tipping the ignition key. This results in a still more favorable condition. The limit between a good and a bad starting behaviour shifts downward to smaller starting torques. The large starter inertia (reduced on the crankshaft) reduces the irregularity of the engine.

Many modern engines exhibit a starting torque of 70 - 80 Nm, whereas only approximately 40 Nm were customary earlier. Therefore, current DMFW concepts also work without problems for many three cylinder engines although these problems seem critical from the viewpoint of irregularity.

The starting behaviour can be improved by the measures cited in Figure 11.

- **High engine starting torque**
- **Starter up above resonance speed left in position**
- **High starter speed**
- **Damping (friction hysteresis in the DMFW)**
- **High primary flywheel mass**
- **Small secondary flywheel mass**
- **Flat spring rate of the rotation damper**

Figure 11: Measures to improve the starting behaviour

In the early years of DMFW development, the high load of the components from the resonance breakthrough was a primary issue. Since the components had large dimensions in comparison to a conventional clutch disc, the flange for example, another cause for excess torque was recognized relatively late. Only as the occurrences of resonance were gradually improved and when attempts were made to design the components somewhat smaller for cost reasons was it discovered that a sudden load generated similarly high peak torques.

When the clutch was engaged very quickly, impacts occurred if there was a great difference between the speeds of the engine and the transmission shaft. These types of quick engagements occur during very sporty, fast shifting, but also during incorrect operation, such as slipping from the clutch pedal.

The result is illustrated in several phases in Figure 12. The rotational movement of the drive train is depicted as a linear model to obtain a better overview.

Assuming that the two flywheel masses of the DMFW, which are coupled together via the DMFW torsion damper, move toward the right at a high speed and the remaining drive train stands still, the clutch is closed suddenly. The secondary flywheel mass is thus quickly slowed, while the primary flywheel mass is only slowed later because of the very weak torsion damper. Therefore, a relative movement occurs between the two flywheel masses that can become so large that the masses can impact upon one another with high speed. This can lead to very high peak torques.

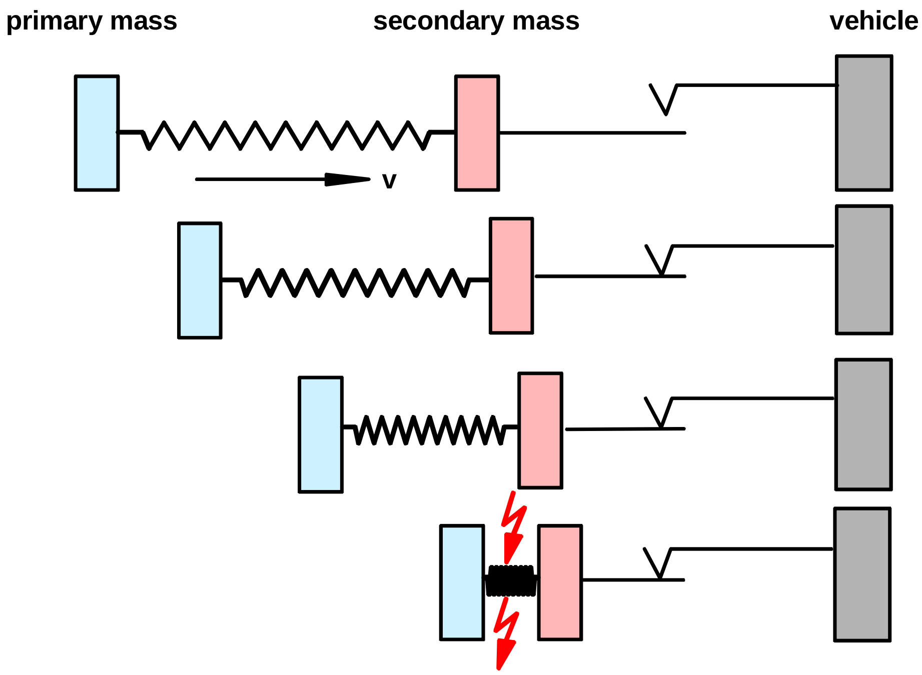

Figure 12: Impact load after quick engagement

Figure 13 illustrates the torques occurring between the flywheel masses immediately after the clutch closes as it would occur for an ideal torsion damper with a very long characteristic curve without impact. These can be more than double the engine torque depending on the distribution of the mass.

Typically, the characteristic curve of a DMFW torsion damper ends at approximately 1.3 times the engine torque. The damper then blocks and an impact occurs that reaches up to 20 times the engine torque.

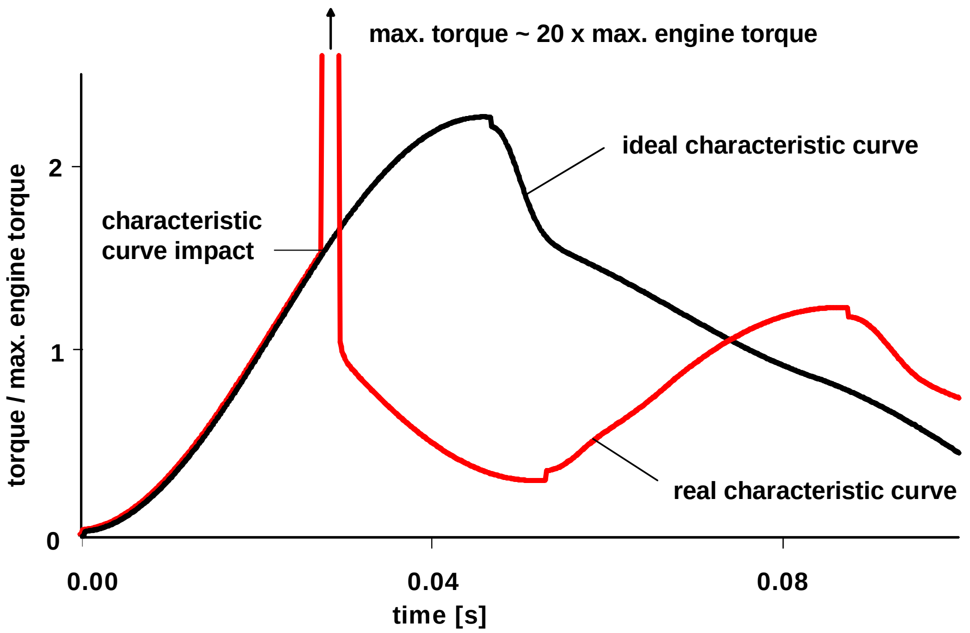

Figure 13: Torque curve between the primary and the secondary flywheel masses after quick engagement for ideal, infinitely long characteristic curve, as well as for the real characteristic curve with an impact torque of approximately 1.3 times the engine torque

Figure 14 illustrates the influence of the engagement time and the impact torque on the peak torques. The engagement time was the parameter varied. The figure illustrates that the peak torques are highly dependent on these parameters. During slow engagement and/or high impact torques, impacts are practically avoided. Hence, the goal is to lengthen the engagement time, for example, by installing a valve in the hydraulic release system.

A peak-torque-limiter is suited for this purpose. It can greatly reduce the impact torques by acting as a relief valve.

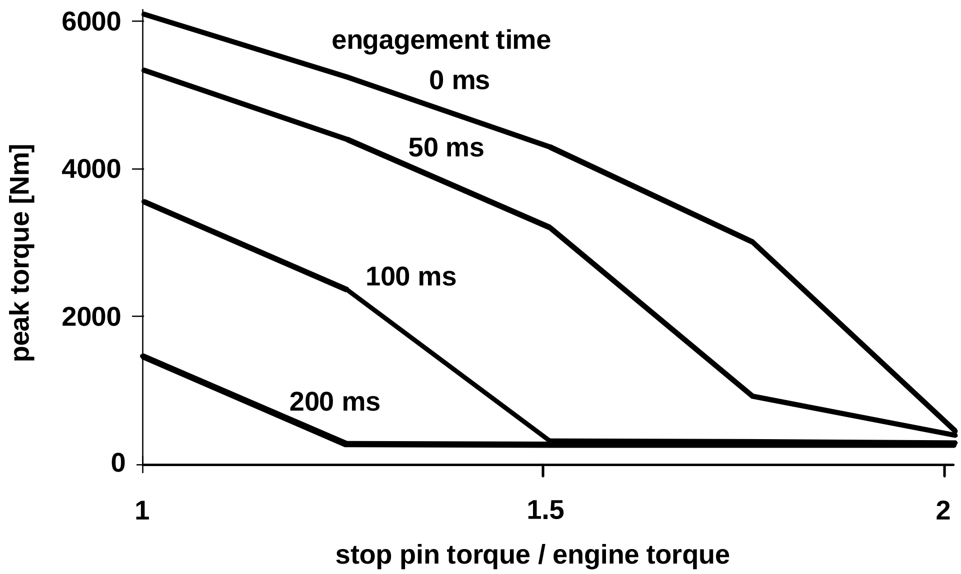

Figure 14: Influence of the impact torque and the engagement time on the peak torques

	time [ms]
• **Mechanical release system with steel pedal**	**15 - 20**
• **Mechanical release system with plastic pedal**	**3 - 7**
• **Hydraulic release system warm**	**30 - 70**
• **Hydraulic release system cold**	**400 - 1000**
• **Hydraulic release system warm, with damping**	**100 - 250**

Figure 15: Typical engagement times for mechanical and hydraulic release systems

Figure 15 illustrates typical minimum engagement times during rapid engagement. Mechanical release systems can engage without slowing, particularly if they have a light plastic pedal. Even a heavier steel pedal reduces the peak torques notably. The favorable, minimum – i.e., long – engagement times are produced by the hydraulic release systems.

If the peak torques cannot be limited over the engagement time, other measures must be used. Figure 16 lists the known measures. A torque limiter, which is connected in series to the DMFW damper, has proven the most effective.

- **Stop pin torque high**
- **Peak torque limiter damping in release system**
- **Spring rate high (shorten angle)**
- **Torque limiter**
- **Reduce clutch torque**
- **Automated clutch instead of conventional clutch**

Figure 16: Measures to reduce peak torques during rapid engagement

New Generations

In the beginning, it was indicated that a DMFW could result in significant noise and comfort improvements in all vehicles. The apparent additional costs have prevented broad application of DMFW thus far, particularly for smaller vehicles, because the numerous secondary advantages were not yet considered.

Therefore, cost reductions have been the focus of development in recent years. The most important of these reductions will be covered below.

General Cost Reductions

The metal-forming process for the sheet metal parts was improved, leading to machining being rendered almost unnecessary in newer designs. In addition, other cost reductions were achieved through FEA calculations and optimum material selection.

The introduction of the smaller ball bearing was difficult, but in the meantime has proven itself worthwhile in production (Figure 17). There is no intermediate size between the large and the small bearing due to the bolt hole configuration of the crankshaft (either inside or outside of the bearing). This resulted in a large step, which was difficult for many customers.

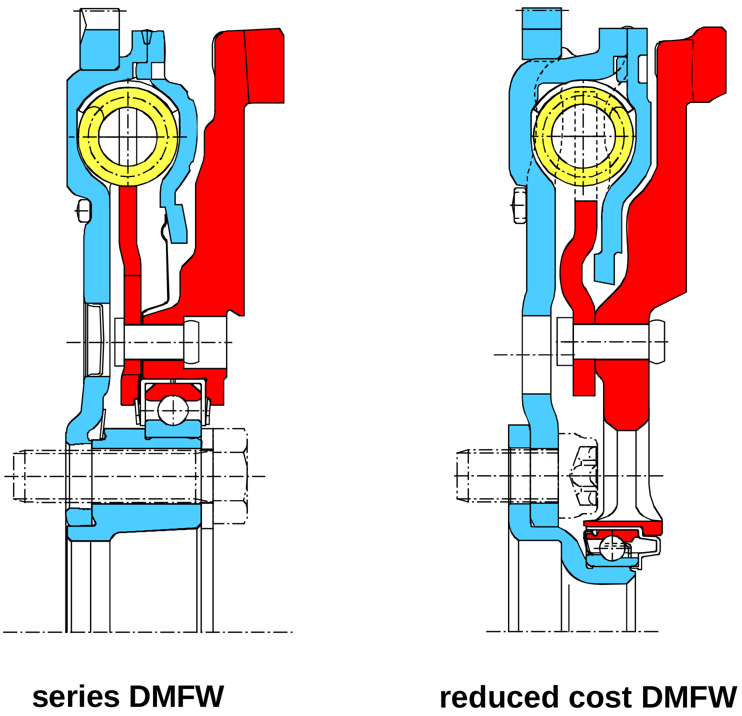

Figure 17: Reduced-cost DMFW with small bearing

In addition, modular construction systems were developed for different customers for which only small modifications to individual DMFW components, such as arc springs or friction control devices, had to be made between the individual engine sizes.

These types of modular construction solutions also require the vehicle manufacturer's assistance, who must also undertake standardization measures, for example with regard to ring gear position.

Bushings

Another cost reduction could be accomplished with bushings (Figure 18). It seemed indispensable to arrange this bushing inside the bolt hole configuration of the crankshaft. When the clutch releases, the entire release force must be supported by the bushing. In connection with the large friction radius, the friction moment was too high, which impaired the isolation. Therefore, LuK recommended that the bushing must be designed to the smallest diameter.

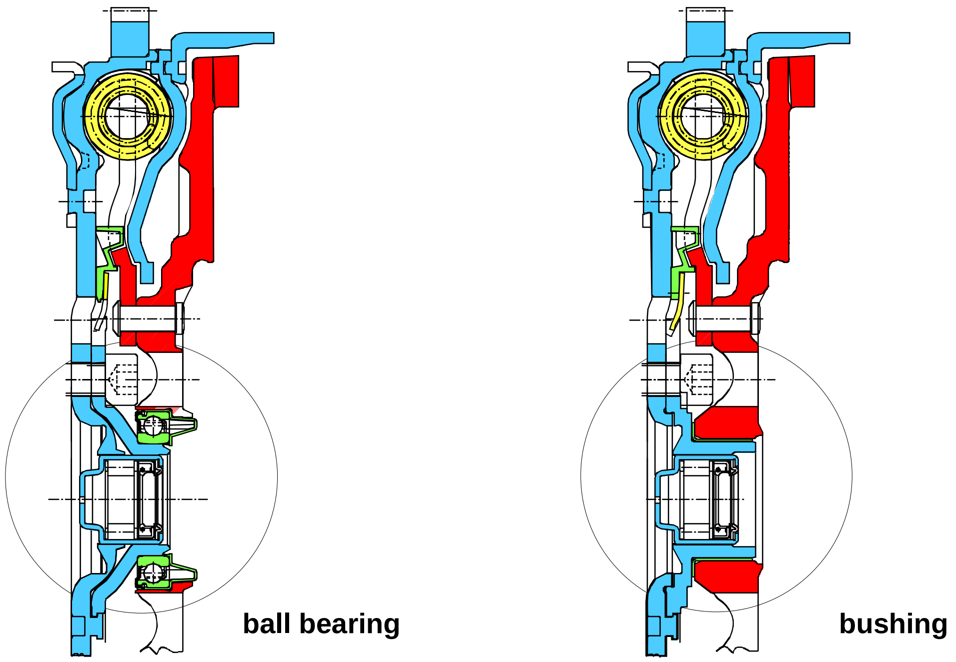

Figure 18: DMFW with bushing

Tests conducted thus far with various bushing designs are promising and a satisfactory service life is expected with sufficient centering accuracy.

DMFW with Dry Damper

In the initial DMFW development, efforts were made to design the torsion damper similar to those in clutch discs. Since the DMFW torsion damper exhibits substantially better vibration isolation than a torsion damper on a clutch disc, the springs in the DMFW had to embody a larger relative vibration angle. The higher wear on the spring guides associated with this change required a switch to grease-lubricated dampers.

Due to the related costs for lubrication for the grease, the seal, etc., LuK conducted a new study to develop a dry-running damper for the DMFW.

We still are not able to say with certainty that the service life will be achieved. But there is reason to believe that our chances are better now than in 1985. LuK has better theoretical and technical testing facilities to analyze the arrangements that are created and to introduce measures against wear.

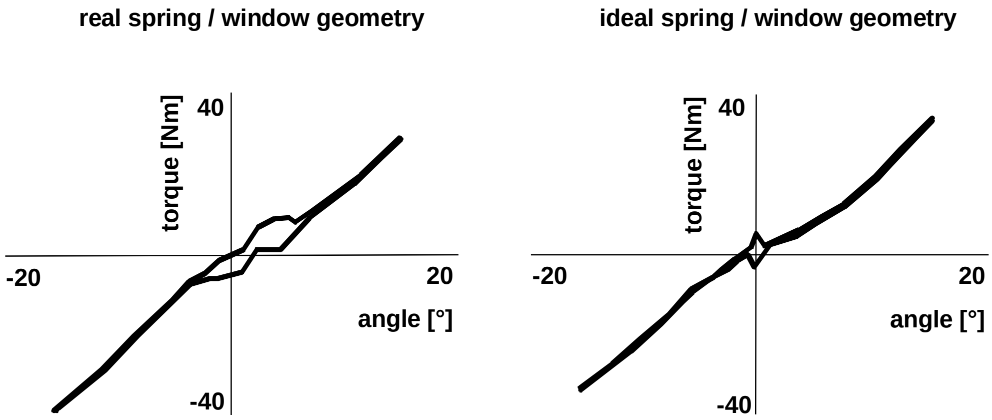

Figure 19: Hysteresis partial loop during torque change

By optimally designing the spring guide, i.e., of windows and spring end coils, the friction work and thus the wear can be reduced considerably, for example, as shown in Figure 19.

Another improvement is achieved if the springs are configured on as small a diameter as possible to keep the centrifugal force low. Based on experience from the early development of the DMFW, a sufficient service life can be expected from the dry torsion damper in the DMFW. The DMFW design is simplified significantly by omitting the grease lubrication.

If all of the savings potentials are combined, then a DMFW results as illustrated in Figure 20. The inner coil springs no longer permit the customary flat characteristic curve. However, inspections in several vehicles have shown that these versions of the DMFW for four and six cylinder gasoline engines exhibit good vibration isolation. The realizable spring rate does not seem to be adequate for four cylinder diesel engines. The dry DMFW in this form is not currently possible for this type of engine.

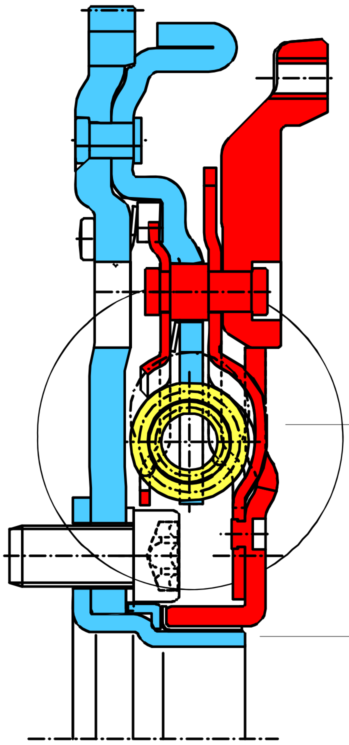

Figure 20: Future DMFW

Alternative Possibilities for Elimination of Torsional Vibrations in the Drive Train

Alternatives to the DMFW are constantly being sought – even at LuK.

The torsional vibrations can be filtered out, for example, via a slip clutch. This does not, however, achieve the vibration isolation of the DMFW, as Figure 21 illustrates. This is explained in the presentation on the automation of clutches [6].

Another theoretically interesting possibility that has recently met with great response in the popular scientific press shall now be explored [7, 8].

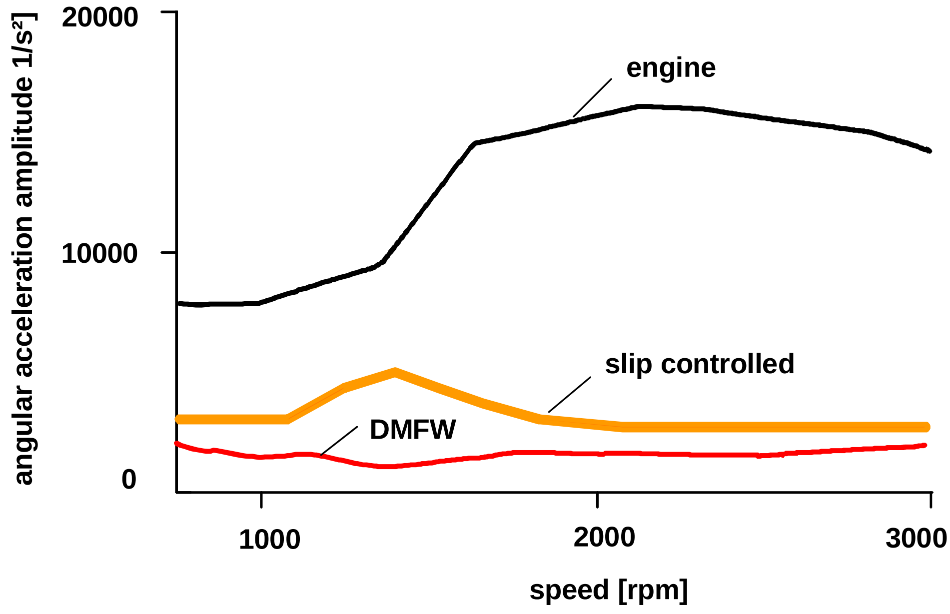

Figure 21: Comparison of the vibration isolation of a dual mass flywheel with a controlled slip isolation system

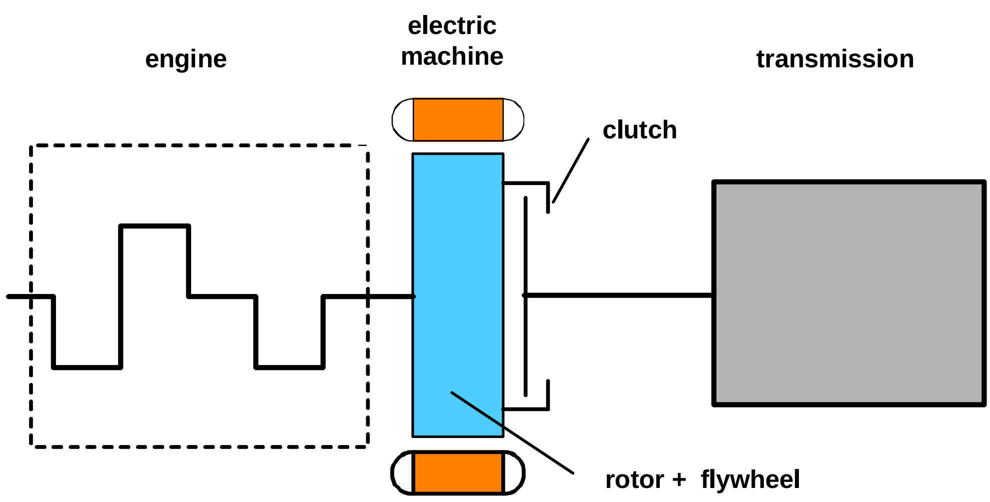

Figure 22: Schematic representation of the crankshaft starter generator

It deals with the possibility of reducing the torque variations by deliberately generating counter-torque with an electric machine. This seems easy to do if - for a completely different reason - a crankshaft starter generator should be used. These crankshaft starter generators, which have been developed by different companies, combine the starter and generator in one machine, which is installed between the engine and transmission instead of the flywheel (Figure 22). Such an electrical machine could work as a generator and draw the corresponding amount of torque from the crankshaft whenever the engine delivers too much torque after ignition, in order to give back the torque as an electric motor during the compression phase. Theoretically, the torque curve could be completely flattened out.

Figure 23 illustrates the torque curve over the crankshaft angle for a four-cylinder diesel engine. Based on a speed of 1500 rpm, a crankshaft angle is determined for one half rotation.

It can be seen which energies must be considered based on the areas above and below the middle torque line.

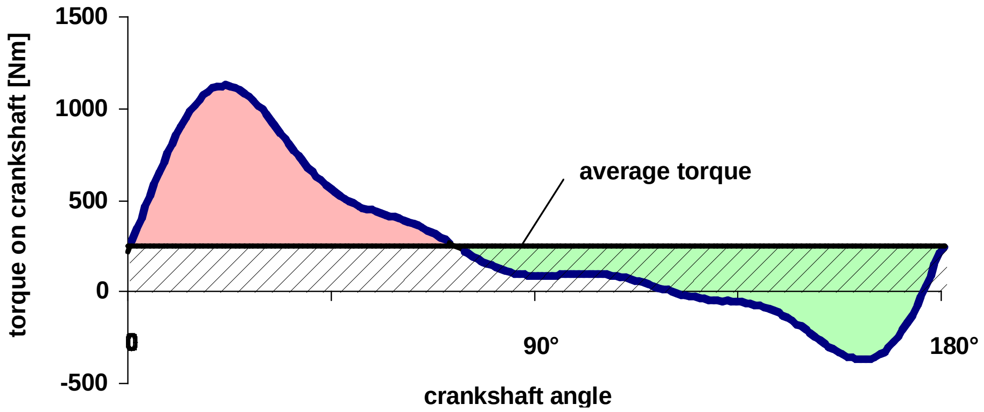

Figure 23: Torque curve over crankshaft angle

The energy to be taken away by generating a current in case of excess torque is represented by the red area. This must be stored for a short time, for example, in a capacitor.

During the compression phase, this energy must be returned via the electric motor (green area).

To estimate which amounts of energy are involved, the area corresponding to the average torque, which corresponds to the work of the combustion engine, was also shaded.

A simple comparison of factors shows:

The electric power, which must be transported back and forth, achieves the same order of magnitude as the average engine power. In other words: some 10 kW are constantly being generated in the electric machine, balanced out, stored in the capacitor, released again, sent via an inverter to then drive the electric motor. Even if an implausibly high efficiency of 98 % is assumed for each individual step, the overall efficiency would only be approximately 88 %. That means 12 % of the electric power transported back and forth, which is in the order of magnitude of the combustion engine power, or a significant amount of kW, would be converted to heat.

Even if it is assumed that full torque compensation is unnecessary because the DMFW cannot completely eliminate the vibrations, the energy balance of a corresponding electrical machine would fall extremely short with a diesel engine.

Gasoline engines are more favorable here (Figure 24). Nevertheless, this does not change the fact that there are enormous electrical losses with active torsion excitation damping from an electrical machine.

vehicle	amplitude of the torque variations [Nm]	
	idle	drive at 1500 rpm
four cylinder diesel	300	700
six cylinder diesel	280	700
four cylinder gasoline	35	290
six cylilnder gasoline	35	300

Figure 24: Typical torque amplitudes on the crankshaft

By contrast, the DMFW achieves fantastic values in this regard. Due to the vibration angle within the DMFW, some energy is also lost because of the friction generated. For the unfavorable case of a four-cylinder diesel engine at 1500 rpm, the loss from the hysteresis cycle is the same as for the corresponding vibration angle. This is a loss of approximately 50 W, or a factor of 100 less than with the above-described active damping.

LuK therefore goes on the assumption that a mechanical damping system similar to the DMFW is still needed with the use of crankshaft starter generators.

Summary

In the European High Group, the DMFW has become quite successful and is just about to penetrate into the mid-size class. Early developments for small engines below 1.6 liter engine displacement give reason to expect that there will be numerous DMFW applications for this area in a few years.

The DMFW offers the best vibration isolation, which cannot be provided by any other system today. In addition to the familiar advantages, the elimination of gear rattle and droning are additional advantages, which were not considered as much in the past.

Lower transmission loading can be expected by filtering out changing torque portions, particularly for diesel engines. Crankshaft vibrations (torsion and bending) are reduced. This allows for a new crankshaft design. It must be noted that the engine irregularity is likely to increase due to the low flywheel mass of the DMFW.

The elimination of gear rattle prevents numerous customer complaints who fear that their transmission could be damaged, causing expensive disassembly costs during the warranty term.

Fuel consumption and emissions are reduced by driving in a lower speed range.

The additional system costs for an optimized DMFW are still higher than for a conventional solution. If the secondary advantages are considered, many DMFWs are already cost-neutral.

Nevertheless, LuK is still trying to reduce the cost of the DMFW. This should lead to new fields of application. In addition to the customary rationalization measures and fine tuning, a transition will be made in the coming years from a ball bearing to a bushing. Furthermore, work will be conducted on dry DMFW dampers, which are not being considered for critical engine sizes, but which can produce a cost efficient DMFW concept for a large portion of vehicles.

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