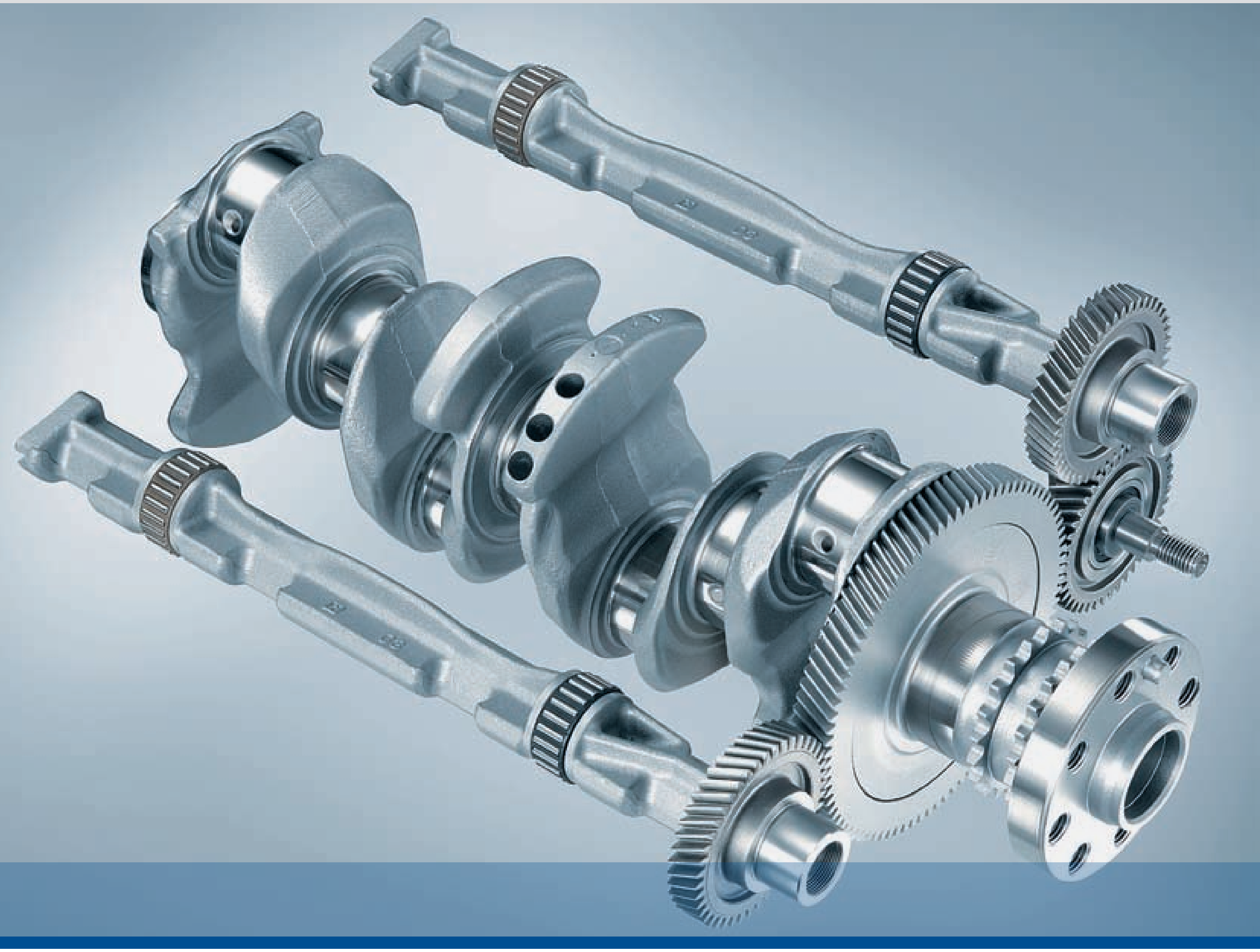

The Integrated Balancer Shaft System of the New BMW Four-Cylinder Diesel Engine

The numerous demands on modern internal combustion engines result in conflicting requirements with regard to comfort, power density, performance, exhaust emissions and fuel efficiency. By introducing an integrated balancer shaft system in the new BMW four-cylinder diesel engine, BMW has taken a major step towards meeting these requirements.

1 Introduction

In March 2007 BMW launched an all-new four-cylinder diesel engine on the market. The concept features and performance characteristics were previously explained in detail in the 11/2007 and 12/2007 issues of MTZ [1].

A major challenge for the new development was the compact engine design which allows the engine-transmission unit to be installed on a wider range of vehicles with no need for radical modification of the basic engine specification. The catalog of requirements for the balancer shaft system derives from additional requirements, such as minimization of engine vibration, reduction of specific fuel consumption, optimization of cold-starting performance and improvement of overall engine acoustics. These are:

- 85 % balancing of inertial forces, 30 % balancing of alternating moments of inertia
- suitability for all-wheel drive of all vehicle derivatives
- minimization of drag power
- avoidance of oil churning losses and oil foaming
- no pitching moment about the engine‘s transverse axis
- optimized balancer shaft acoustics
- low mass moment of inertia
- systematic implementation of the common parts principle within the four-cylinder family
- minimization of weight and cost.

2 Conceptual Design

2.1 Concept

Most four cylinder engines use “add-on” units for balancing the masses, where the unit is positioned inside the oil pan [2]. In contrast to these solutions, the balancer shaft system of the new BMW four-cylinder diesel engine has been integrated in the aluminum cylinder crankcase. From a conceptual standpoint, the balancer shaft layout lateral to the crank mechanism has three significant advantages. The balancer shaft can now be installed on all vehicle types, including all-wheel-drive versions, thus completely avoiding the churning losses which occur particularly during the warm-up phase at low oil temperatures and due to the form of the shafts, a reduced mass moment of inertia can be achieved.

2.2 Engineering Design

The balancer shaft located on the input side is driven directly by the crankshaft gear. The vertically offset shaft positioned on the output side is driven through an idler gear, on account of the necessary reversal in the direction of rotation, **Figure 1**. Due to the constraints on installation space the intake-side balancer shaft is located within the path of movement of the conrod. CAD kinematic methods were used in order to determine how much of a recess was needed in the balancer shaft to ensure sufficient clearance in all rotational positions relative to the conrod. For the first time on passenger car diesel engines, friction enhanced needle bearings are used for radial mounting of balancer. The open cageless needle bearings are held in an axial position by lateral shaft bearing flanges. The forged shafts have a successively stepped bearing diameter in an axial direction. Both the bearings and the forged shafts are configured as common parts. The tempered outer races, which are press-fitted into cylinder crankcase bearing seats two and four, constitute the outer races of the roller bearing. The idler gear is mounted in two rows of grooved ball bearings on a radially positionable axis. The balancer shaft system is driven through a gear ring attached to the crankshaft by shrink bonding.

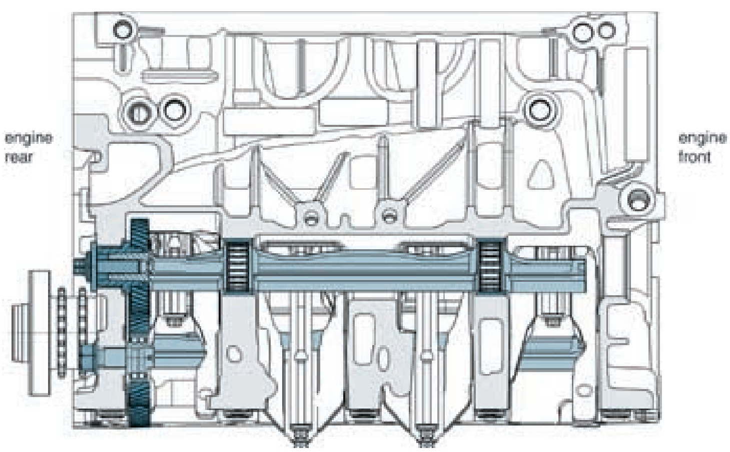

Figure 1: Arrangement of the balancer shaft unit in the cylinder crankcase

The Authors

Dipl. Ing.
Georg Gruber
is designer at the Basic Engine Department of the Diesel Engine Development Center, BMW Group Steyr (Austria).

Dipl. Ing.
Mario Prandstötter
is computational engineer at the Simulation/CAE department of the Diesel Engine Development Center, BMW Group Steyr (Austria).

Dipl. Ing.
Robert Hollnbuchner
is test engineer at the NVH Acoustics department of the Diesel Engine Development Center, BMW Group Steyr (Austria).

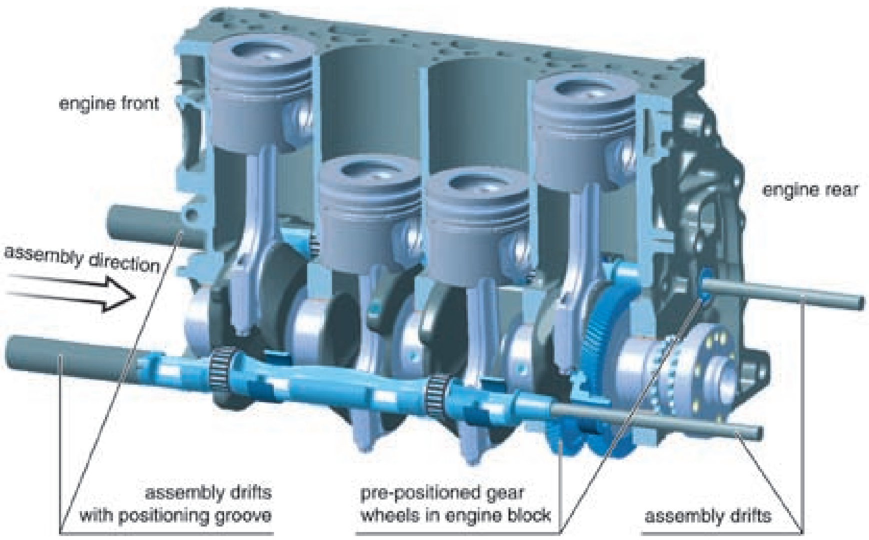

Figure 2: Insertion of the balancer shafts into the cylinder crankcase using assembly drifts

3 Assembly

The balancer shaft together with the pre-assembled needle bearings and gears are delivered to the engine assembly line in specially designed transport containers and assembled almost entirely automatically by means of a sophisticated process. Both shafts are simultaneously moved into position using assembly drifts and subsequently inserted from the front end of the engine into the cast „balancer shaft tunnel" of the crankcase, **Figure 2**. The sintered gears on the transmission end, the idler gear and the crankshaft, together with the gear ring are pre-positioned and brought into engagement in the housing. In the dead center position of the crankshaft, both shafts are connected to the gear wheels by means of a tapered press-fit coupling. Together with the screw coupling and the thrust discs, they form the axial bearing of the system. A correct phase angle is maintained between the balancer shafts and the crankshaft by means of locating grooves on the shaft ends.

4 System Behavior

4.1 Vertical Offset

The four-cylinder inline engine is subjected to aggregate free second-order alternating moments, in addition to oscillating free second-order inertia forces. These forces and moments are absorbed by the engine and transmission mountings and are partly responsible for noise and vibration transmission to the body and the vehicle interior. Generally speaking, for conceptual design reasons, only the oscillating inertial forces are balanced. In the new BMW four-cylinder diesel engine, additional balancing of alternating moments of inertia is provided by the vertically offset arrangement of the two balancer shafts. The second-order moment acting freely on the engine mounting is composed of the alternating moment of inertia and the charge cycle moment and, for this reason, is dependent on both engine speed and load. To achieve an optimum configuration it is necessary to take into account the effect of the balancer shaft system across the entire characteristic map and thereby resolve the conflict of goals by choosing an appropriate degree of balancing for the alternating moments of inertia. For instance, although 100 % balancing of the alternating moments of inertia in overrun mode would have a positive overall effect, it would result in excessive overcompensation under engine load. By using dynamic computational tools it was determined that the optimum degree of balancing with regard to the resultant forces acting on the engine bearings was 85 % for inertial forces and 30 % for alternating moments. A comparison of balancer shaft systems with and without vertical offset shows significant differences, whereby the solution with vertical offset exhibited less vibration and better acoustics at engine speeds above the vibration-absorption point, **Figure 3**. The vibration-absorption point is defined as the point at which the total of all alternating moments reaches a local minimum. In addition to this, lower forces in overrun mode and higher forces under full throttle indicate a greater dependence on engine load than engine speed, particularly in the middle rpm-range. Consequently, this produces noticeably dynamic load feedback from the engine under acceleration.

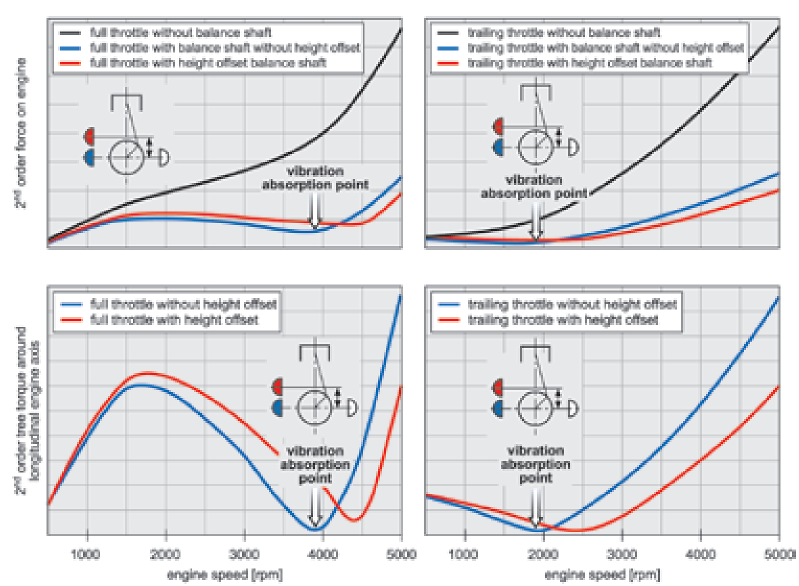

Figure 3: System behavior of balancer shaft unit with / without vertical offset

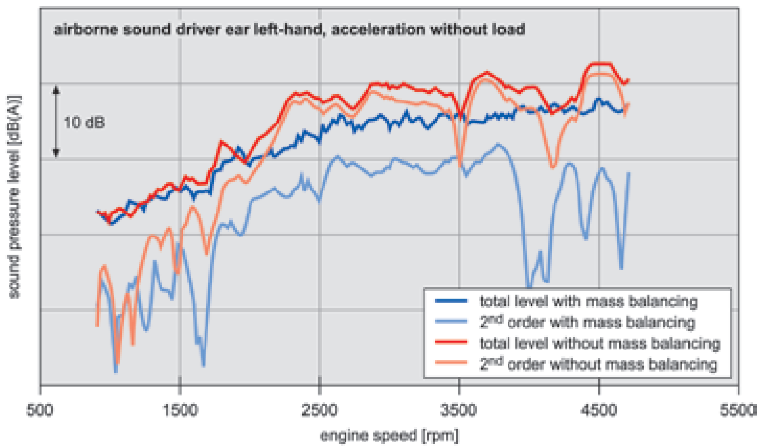

Figure 4: Sound pressure level in the vehicle

4.2 Center of Gravity of the Balancer Shaft

As in the case with balancer shaft systems without vertical offset, the center of gravity of the shaft imbalance was shifted close to the center of the crankshaft in the new four-cylinder diesel engine so as to minimize pitching moments about the engine's transverse axis. Likewise, to avoid moments about the engine's longitudinal axis, an identical value was chosen for the clearance between the shafts and the crankshaft axis in the transverse direction of the engine on the input and output sides.

4.3 Effect

The effect of the new mass balancing system in the vehicle is noticeable across the entire engine speed and load range. The interval between orders necessary to create a positive perception in the vehicle interior is achieved by reducing the sound level by over 10 dB in the second engine order, **Figure 4**. The above-stated degrees of balancing with regard to inertia force and mass moment have been shown to produce very good results with regard to vibrations, acoustics and load feedback. In terms of system behavior, they accentuate the sportiness and dynamics of the engine.

5 Balancer Shaft Configuration

A particularly tough challenge with regard to trouble-free operation of the gear weel drive and bearings was that of shaping the balancer shafts and distributing mass. The design objective was to minimize angular deviations in the bearings and flexure at the gear position resulting from speed-dependent centrifugal forces. The requirements for long life and minimum torsional backlash under meshing were met by optimizing the distribution of masses along the shaft axis. The resulting flexural stresses in the bridge adjacent to the bearings were minimized by shaping the balancer shaft accordingly. **Figure 5** shows in 200x magnification the flexure line calculated by using numeric methods and the resultant flexural stresses at an engine speed of 6000 rpm.

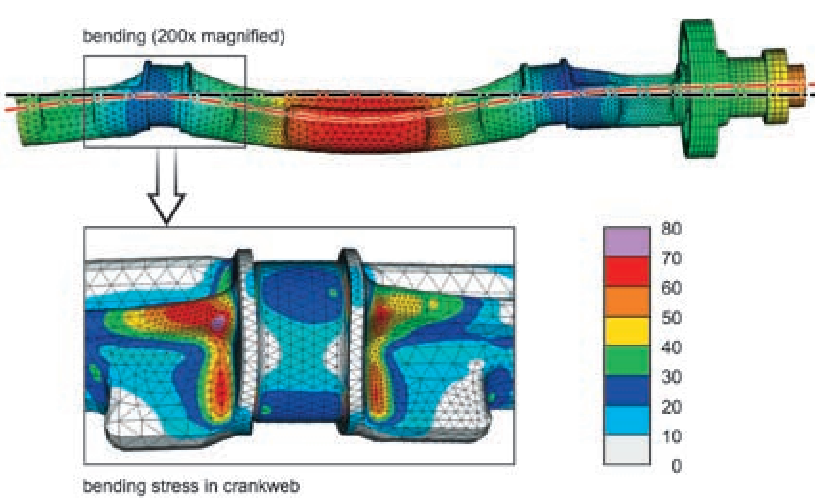

Figure 5: Flexure line and flexural stresses at n_{engine} = 6000 rpm

6 Acoustics of the Balancer Shaft Drive

6.1 Gearing

The decisive factor with regard to the configuration of the balancer shaft drive with gear steps was that of minimizing tonal noise in the gear meshing frequency range and rattling noise on gear engagement as a result of torsional irregularity in the driving crankshaft.

By employing topologically optimized helical gearing and reduced flexure in the region of the drive gears thanks to intelligent balancer shaft design, the gear meshing frequency is not actually noticeable inside the vehicle. The amount of mass inertial moment to be transmitted to the gear steps is reduced considerably by the slim, elongated shaft design and by the unconventional distribution of masses to the input and output sides. Firstly, this reduces the engagement shock responsible for producing rattling noise and secondly it allows for the first time the use of high-strength sintered metal for the balancer shaft gears of diesel engines. The good damping properties of the material provide not only a noticeable reduction in sound levels, but also, more importantly, result in a subjectively more pleasant sound than steel gears. This, coupled with a smallest possible backlash setting, reduces the airborne sound radiation of the balancer shaft unit by up to 5 dB over a wide rpm range, **Figure 6**.

6.2 Setting the Torsional Backlash

The idler gear for reversing the direction of rotation of the output-side balancer shaft is designed to be radially positionable, in order to allow controlled backlash adjustment. Torsional backlash in relation to the other gears is initially eliminated during the assembly process through radial press-fitting of the idler gear by means of a molybdenum-carbon compound coating with a close-toleranced layer thickness partially applied to the circumference of the gear. During the subsequent low-temperature test, this coating becomes separated from the metal surface resulting in a narrow tolerance band with regard to torsional backlash, **Figure 7**. This BMW-patented process has already been used on the predecessor engine and avoids the more laborious process of adjustment by spacer plates. Tooth flank backlash can be further enhanced by optimally positioning the gears in relation to the unbalanced masses of the balancer shafts. In this patented BMW process, the selectively aligned, eccentrically ground and subsequently marked drive gears are positioned in the assembly process in such a way that the effect of the considerable shaft bearing play on torsional backlash is equalized under operating conditions. The result is consistently optimal gear engagement conditions in all angular positions of the balancer shaft.

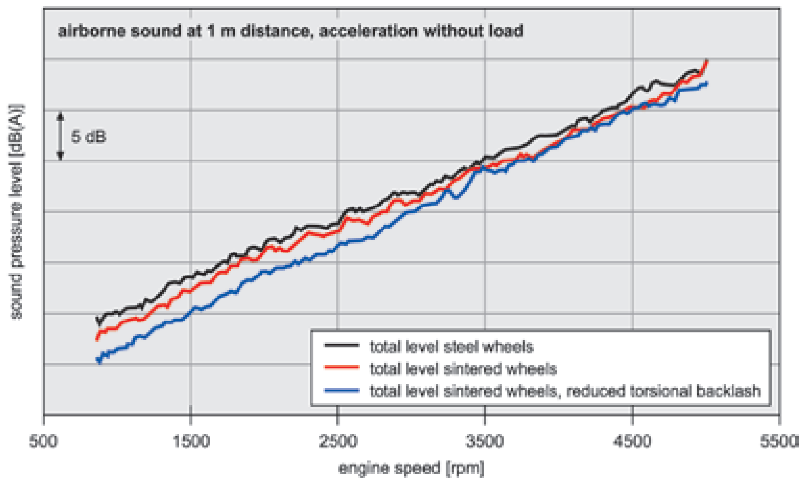

Figure 6: Sound pressure level of balancer shaft gearing, effect of material and torsional backlash

7 Roller Bearing

7.1 Friction

The use of roller bearings for the first time in a balancer shaft system on a four-cylinder diesel engine is a BMW innovation which, due to the considerable reduction in friction, is a very good example of the „Efficient Dynamics“ philosophy. A special feature of roller bearings is their very low power input compared to journal bearings of the same size, due to their rolling action. **Figure 8** shows the reduced drag torque on the overall balancer shaft system at different oil temperatures. Noteworthy features are the efficiency advantage of the roller bearing – up to 70 % across the entire rev. band – and the negligible effect of oil temperature. In addition, considerable potential has been exploited by dispensing with a supply of pressurized oil directly to the radial bearings and by avoiding oil churning losses. The fuel saving in the ECE cycle test is over 2 % with this integrated roller bearing concept.

7.2 Lubrication

The oil spray present in the cylinder crankcase under operating conditions is sufficient to supply the needle bearings. In combination with oil pockets in the needle bearing cage, the oil spray ensures an even distribution of lubricant both to the inner and outer races of the bearing unit. The dual-row grooved ball bearings of the idler gear are also lubricated with oil spray only. The axial bearings of both balancer shafts are supplied with pressurized oil through a spray oil port. The problems commonly associated with the „add-on“ concept with regard to oil gas content and oil foaming can be completely eliminated with the integrated configuration.

7.3 Functional and Endurance Reliability

The bearings are designed in association with the bearing specialists according to the classic roller-bearing calculation and in accordance with the given constraints on installation space. To ensure the durability of the balancer shaft system, special variant and tolerance limit sample tests were conducted by means of drag

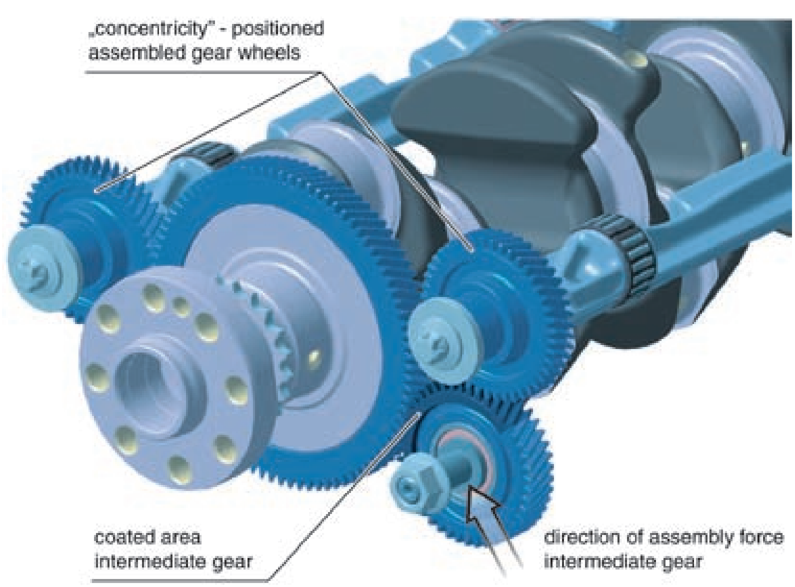

Figure 7: Setting the torsional backlash for optimal gear meshing acoustics

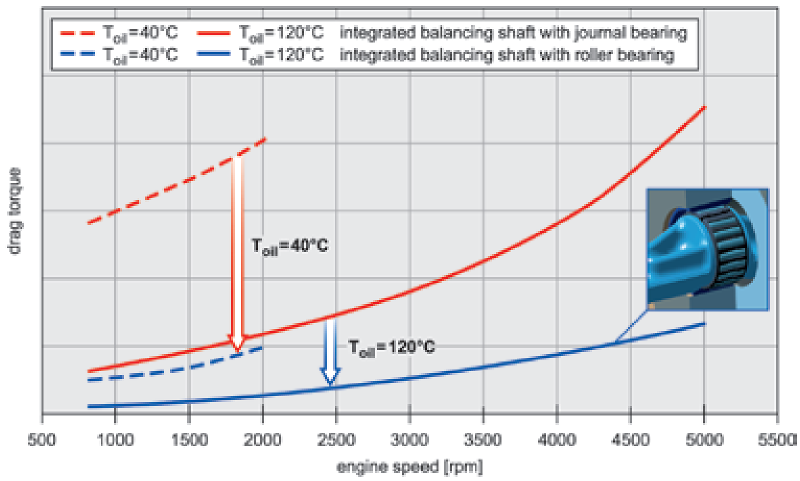

Figure 8: Reduction in drag torque, comparison of journal bearings and roller bearings

endurance tests and powered high-speed tests in addition to conventional endurance testing. The bearings and gearing are subjected to maximum stress at high engine speeds in particular.

An extensive RNT analysis (radionuclide technique) provided vital information with regard to the effect of oil viscosity and the wear resistance of the bearing. The oil temperature in the bearing region was determined at various engine operating points using a thermographic camera. A balancer shaft equipped with a telemetry transmission unit and various sensors allowed the measurement of temperature and stresses on the bearing inner races. This delivered important information which was used to make an appropriate choice of materials and for defining the hardness and annealing parameters. A high-strength, induction-hardenable forged steel is used as a shaft material. All the special requirements with regard to the hardness and microstructure of the bearing race are thus met.

7.4 Acoustics of the Roller Bearing

Operational bearing clearance and the characteristics of the bearing race surface are particularly important as far as optimal roller bearing acoustics are concerned. Bearing play is temperature-dependent due to the different thermal expansion coefficients of the aluminum gear case and the steel outer races. Taking into consideration the boundary condition which requires a minimum amount of play at low temperatures, the operation bearing clearance is kept as small as possible by minimizing the manufacturing tolerances and optimizing the design of the outer race cover.

Processes such as finishing or honing are essential to the manufacture of roller bearing races. Even the smallest deviations beyond the limit curve of permissible ripple amplitude would result in acoustic abnormalities in the bearing unit. Production-flanking acoustic measurements ensure that delivered engines are of an appropriately high quality.

8 Weight

The balancer shaft unit has resulted in a significant reduction in total engine weight compared to the predecessor engine. By eliminating the balancer shaft housing and by using weight-optimized shafts and gears, a weight saving of over 45 % has been achieved compared to equivalent „add-on“ concepts. The complete unit with crankshaft gear ring weighs 4.5 kg. Furthermore, by reducing the number of component parts and systematically implementing the common parts principle, the total cost has been cut by over 30 %.

9 Summary

By fully integrating the balancer shaft unit into the cylinder crankcase, BMW has set a pioneering trend. The vertically offset arrangement provides an additional improvement with regard to vibration comfort, particularly at operating points relevant to the customer. A significant contribution to improving the fuel efficiency of the overall engine was made through the use of roller bearings, by avoiding oil churning losses and by slashing weight. The characteristics typical of the BMW diesel engine – dynamics, low vibrations and high fuel efficiency – have been enhanced through the use of this balancer shaft system.

References

[1] Steinparzer, F.; Mattes, W.; Nefischer, P.; Steinmayr, T.: The new BW four-cylinder diesel engine. In MTZ 68 (2007), No. 11 and 12

[2] Stastny, J.; Ratzberger, R.; Fessel, C.; Keber, A.: The Balancer Shaft Unit of the New BMW Four-Cylinder Diesel Engine. In MTZ 53 (2002), No. 3