Opportunities for Reducing CO_2 Emission by Using Rolling Bearings in Engines

Measures to reduce friction in internal combustion engines are moving up the agenda for developers. This article presents the opportunities offered by replacing plain bearings with rolling bearings, using crankshafts and camshafts as examples. The rolling bearings in balancer shafts are described in close detail to demonstrate the outstanding cost/benefit ratio achieved with this measure. In addition to avoiding mechanical losses, the approach being pursued at INA creates a whole host of other opportunities for optimisation that may result in a reduction in CO_2 emissions.

1 Introduction

Friction minimisation in the drive train is gaining in importance in the development of efficient drive systems. The replacement of sliding bearings with rolling bearings brings about significantly reduced power losses. Nonetheless, the rolling bearings that were previously widespread in engine design have been largely superseded by plain bearings. Although they were undoubtedly sound at the time, the reasons behind this move must be called into question on the basis of developments in the field of rolling bearings and must be re-evaluated for each individual bearing position.

Due to its sheer size and the distribution of friction, the most obvious starting point is the crankshaft, with its main and conrod bearings [1]. The number of bearings on the camshafts of modern engines makes it particularly interesting to determine the potential of reducing friction at the camshaft. Furthermore, as the use of balancer shafts in passenger cars is becoming more widespread due to the increasing need for improvements in noise, vibration and harshness (NVH), the rolling bearing concept and its friction-saving potential must be evaluated under these specific load and operating conditions.

2 Rolling Bearings for the Crankshaft

The substitution of the crankshaft plain bearings (main bearings + crank pin bearings) by rolling bearings in series production passenger car applications is currently not state-of-the-art. Previous implementations have not been permamently accepted for various reasons. Given the current discussions on CO_2 emissions, however, endeavours have been resumed in this direction, inspired in particular by the 5.4% fuel saving in the NEDC on a four-cylinder petrol engine with a roller-mounted crankshaft illustrated in [2]. Besides the lower friction level, roller-mounted crankshafts are expected to reduce the requirements regarding pressurized oil flow. Furthermore, such crankshafts are more suitable for the significantly increased number of start-stop operations in the future, due to the lower lubricating oil requirement and the better dry running capability of rolling bearings.

Long-standing experience in the fields of snow mobiles, quad bikes and motorcycles with roller-mounted crankshafts [3], however, mostly applies to two-stroke applications. In these engines, the temperature requirements, especially on the conrod bearing, are significantly reduced by flushing through the crankcase. Furthermore, assembled crankshafts that permit the use of unsplit bearings and specific bearing race materials are frequently installed in the areas mentioned. Nevertheless, these examples suggest that many of the demanding objectives can be met, for example by operating rolling bearings in engine oil with its specific properties and contamination or the use of split bearings for unsplit crankshafts as seen in large-volume boat engines.

2.1 Design Aspects

In the case of an unsplit crankshaft with integrated rolling bearings, the shaft material must not only satisfy the usual requirements for the crankshaft function but must also be suitably prepared as a rolling bearing raceway. The bearing cages must be split, as must the outer races. The steels suitable for such

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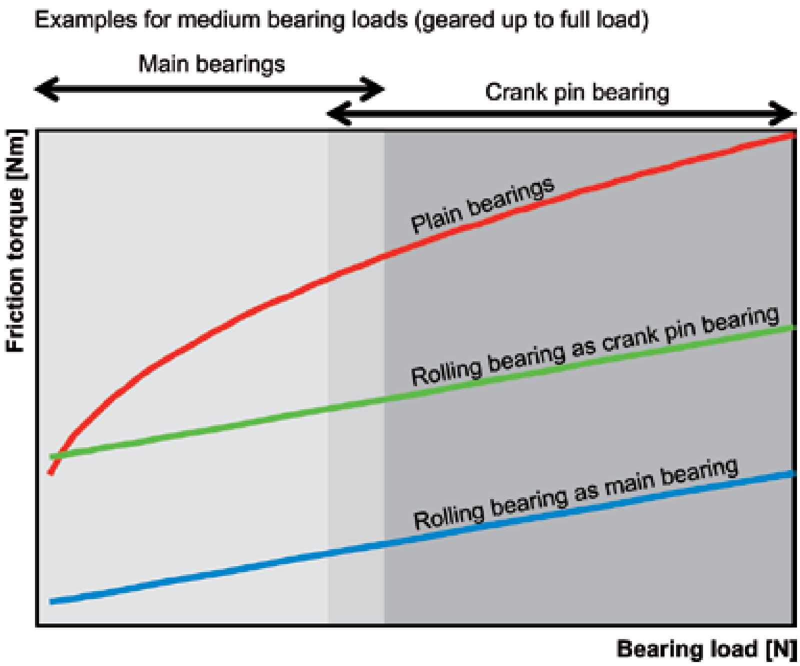

Figure 1: Calculated bearing frictional torque depending on radial load

outer races must harmonise conflicting requirements, such as high rolling contact fatigue (even in the dividing area), good crackability, forgeability and machinability and, last but not least, low material costs.

Besides the bearing life calculation, one of the key factors in bearing design is the identification of suitable clearance. Adequate minimum clearance must be guaranteed under all operating conditions, while the clearance also has a dramatic effect on the acoustic behaviour. The first analytical tools that permit adequate rolling bearing models to be integrated into an overall dynamic system simulation have recently been developed. Practical experience, as published in [1], also indicates that, when it comes to acoustics, an engine with a roller-mounted crankshaft is now a wholly feasible solution.

2.2 Friction-Reduction Potential

In many respects, the conrod bearings have to satisfy far more stringent technical requirements than the main bearings. Installation space is severely restricted in both radial and axial directions, and extreme peak loads and additional centrifugal forces occur.

The increased wear can be countered by employing specific cage designs and coatings, for example copper/silver coatings and, more recently, also DLC coating systems (Triondur).

Friction calculations on individual bearings based on catalogue formulae cannot simply be transferred to this specific application, since the geometry-related influences of the bearing as well as dynamic tilting, elastic deformations and the highly dynamic loads are not included in the formulae concerned. This gap can be closed by using simulation tools, which also significantly increase system understanding. The friction models employed in these programs are suitable for solid body friction and mixed friction, as well as that of elastohydrodynamics (EHD). The bearing durability can be calculated more precisely by integrating the elastic bearing environment. For this purpose, rolling bearing manufacturers are investing heavily in developing specific, proprietary software solutions, for example at Schaeffler KG: Bearinx (static), Caba (rolling bearing dynamics) and Telos (surface roughness in rolling contacts).

With regard to the design feasibility and the specific challenges for the conrod and the expected friction potential, **Figure 1**, the technical effort required to implement the main bearings of the crankshaft as rolling bearings is significantly less than with the conrod bearings.

3 Cam Shaft Rolling Bearings

In most modern engines, the number of camshaft bearing positions is so high that the total frictional losses and thus the savings potential seem considerable. Compared to the crankshaft however, the loads are moderate, so that the expected frictional heat relative to the heat transfer capability of the surrounding components, the camshaft and cylinder head, is quite low. Therefore, there

Figure 2: Split camshaft rolling bearing for one-piece camshafts with small bearing diameters

is no need to supply compressed oil to the bearings when rolling bearings are used. The major portion of this oil has a cooling rather than a lubrication function anyway.

As far as the frictional losses in the camshaft bearings are concerned, both calculative analyses and experimental results on the torque of cylinder heads demonstrate that, in the case of the plain bearings in the lower speed range, bearings are operated in the mixed friction range. At mid to high speeds, by contrast, a separation of the surfaces by a hydrodynamic oil film is achieved and this significantly reduces frictional losses.

3.1 Conventional Camshaft Design

One-piece camshafts with small bearing diameters require the bearings to be split (cage and outer ring), **Figure 2**. To conform to the preferred load direction, the bearing separation plane must be positioned in the area with comparatively little load, so that a reduction in the bearing capacity in the divided area is barely relevant.

Unsplit bearings can be employed for assembled camshafts that have become more popular in recent years. This involves either mounting an inner bearing ring to the shaft or using the main body of the camshaft itself – subject to the appropriate material and manufacturing requirements – as the rolling bearing raceway.

The test-based evidence of friction reduction using camshaft rolling bearings confirms the understanding of the system. In the lower speed range, the losses caused by the mixed friction in the plain bearing can be avoided, though at higher speeds the savings potential is quite limited. **Figure 3** summarises the results of comparative measurements on four different four-cylinder engines.

The engines are fitted with two overhead camshafts. The measurements were taken on one camshaft. The results, however, must also be evaluated in each application individually, taking into account both the secondary effects and the cost/benefit ratio. Secondary effects are, for example, the elimination of the oil supply bores, reduced pressure oil supply and less oil in the cylinder head.

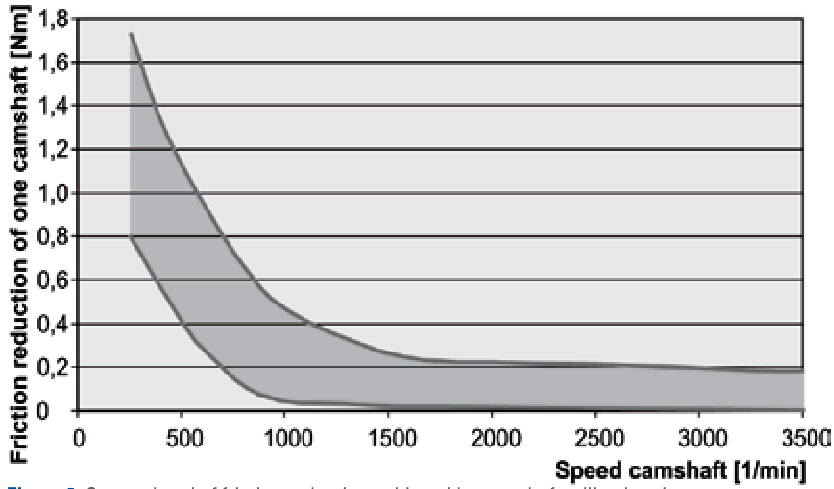

Figure 3: Scatter band of friction reduction achieved by camshaft rolling bearings

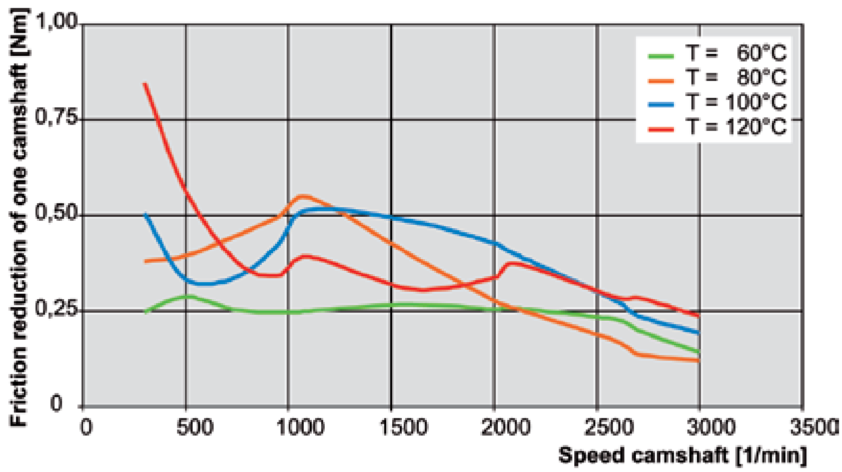

Figure 4: Friction reduction on a tunnel camshaft (single shaft of a DOHC engine)

3.2 Tunnel Camshafts

Despite the friction-related drawbacks of tunnel camshafts, there are still good reasons for using camshafts with bearing diameters that are large enough to allow for an axial assembly into a housing. The reduced number of bearing positions compensates for only part of the system-related friction drawback. In this case, the use of rolling bearings for reducing friction losses is highly promising. The unsplit design with thin-walled inner and outer rings that is possible in this case enables the cam shaft to be used largely unchanged.

Measurements taken on this type of system show a significantly smaller mixed friction range. The friction advantage of the rolling bearing, however, is quite constant over speed in the range between 0.2 and 0.5 Nm, **Figure 4**. In tunnel camshafts, therefore, the higher savings potential coupled with the comparatively moderate complexity of realising the design and manufacture result in an extremely favourable cost/benefit ratio.

3.3 Acoustics

To analyse the effects of a camshaft rolling bearing on engine acoustics, a four-cylinder engine (1.4 litre capacity) in a compact class vehicle was chosen deliberately. Due to the comparatively frugal acoustic insulation, any unfavourable effect of the rolling bearing should be especially noticeable. A direct comparison of acoustic measurements (dummy head on the passenger seat) in various driving situations yields differences between plain and rolling bearings that in almost all cases are below the perceptible limit, **Figure 5**.

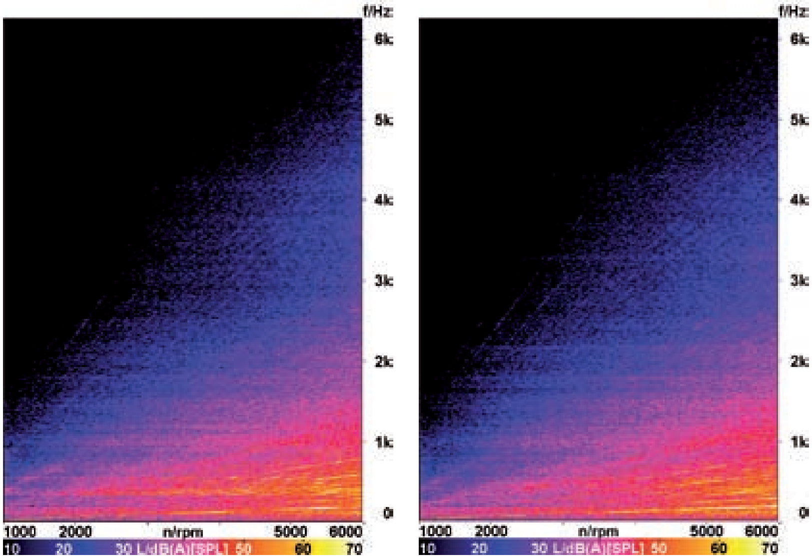

Figure 5: Comparison of airborne sound spectrum versus engine speed (passenger seat)
Left: camshaft with plain bearings; Right: camshaft with rolling bearings

4 Optimisation of Balancer Shaft Systems

4.1 Potentials for Reducing Friction

While the need for improvements in consumption behaviour is clearly in the focus of the public discussion, a permanent optimisation of NVH behaviour is still also expected. Balancing the free 2nd order mass forces of four-cylinder engines requires two counter-rotating balancer shafts which rotate at twice the crankshaft speed and exert considerable forces upon the cylinder crankcase increasing quadratically with speed. Due to the number of bearings required as well as the high forces and high speeds involved, the use of rolling bearings to reduce friction would appear to be the obvious solution.

An initial design of such a rolling bearing arrangement would be based on conventional methods. Subsequently, however, the influence of shaft deformations and housing elasticity on fatigue durability should be considered through additional analyses. Other effects on bearing life include oil quality in terms of its viscosity, contamination and additives, as well as the non-transient peak temperatures actually occurring during operation. Ultimately, the high peak speeds of balancer shafts in four-cylinder engines often necessitate special bearing and/or cage designs.

For cost reasons, the experimental testing of the bearing design is often initially conducted on a separate test stand which, to be practical, uses an arrangement of four balancer shafts driven in a suitable synchronisation in order to compensate for internal inertia forces, **Figure 6**.

The speed capability of the bearing design, the temperature conditions and the bearing life under various influences are analysed in detail on the test rig. A plain bearing variant can also be directly compared with this bearing concept in terms of the required torques, allowing the achievable friction reduction to be determined. **Figure 7** shows a typical example of the torques in an arrangement with two balances shafts in a four-cylinder engine.

The friction reduction of rolling bearings compared to the plain bearing arrangement is in the range of 50% and

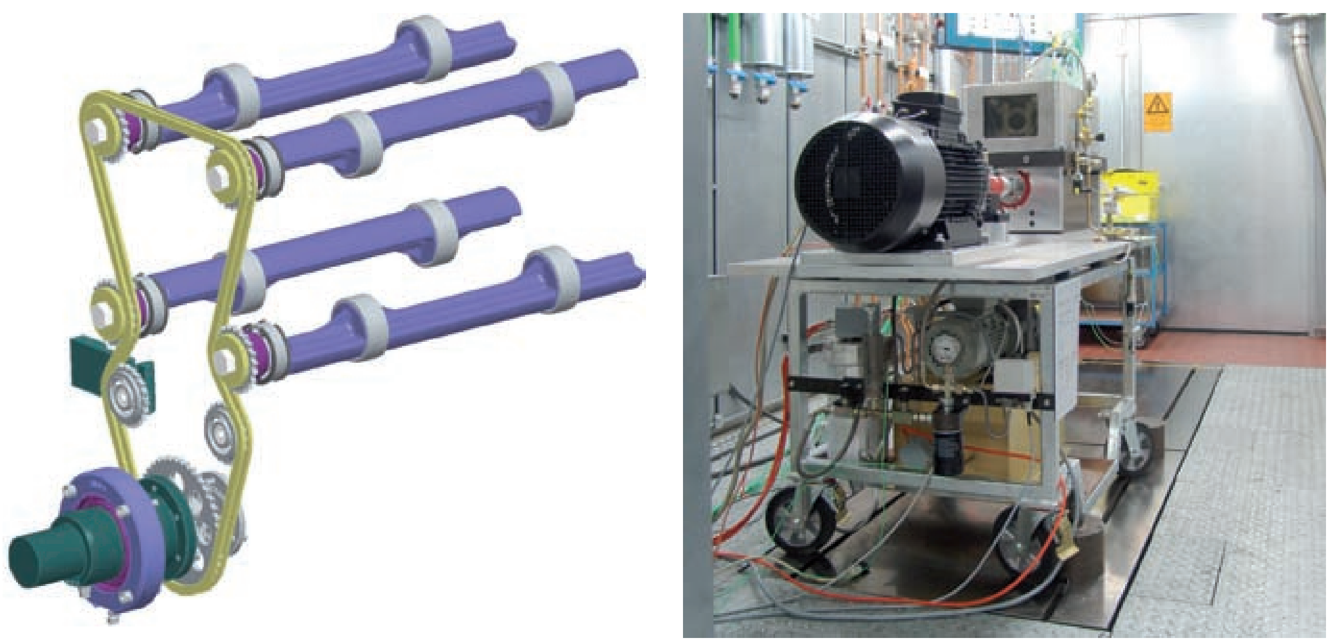

Figure 6: Test rig concept with four balancer shafts and test rig implementation

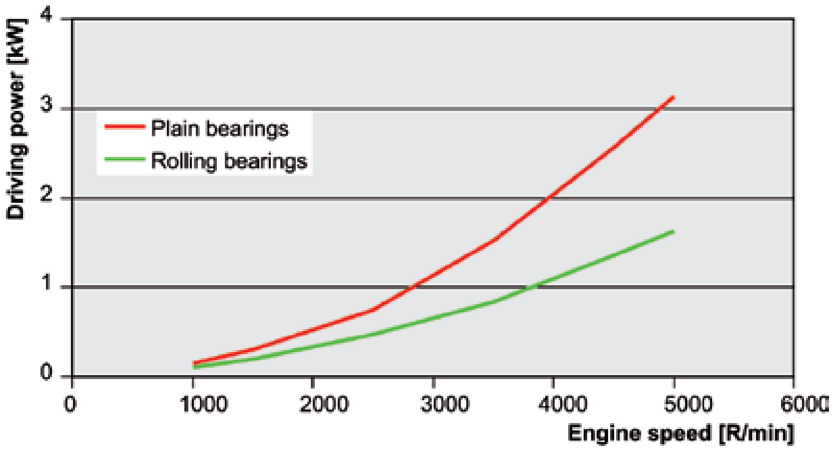

Figure 7: Driving torque of the two balance shafts in a four-cylinder engine (oil temperature 90°C)

above, depending on design. It is remarkably constant over the examined temperature range of 30 to 120°C. Expressed as absolute values, it is more than 1.5 kW at an operating temperature of approximately 100°C in the upper speed range. As well as the associated increases in engine efficiency, this also has positive secondary effects. The heat transfer capability through the surrounding components is often sufficient for the reduced amount of dissipation in the bearings. This in turn eliminates the need to supply pressurized oil to the bearings. Consequently, omission of the supply bores and reductions in oil pump capacity as well as oil cooling requirements are positive side effects. Development engineers of various car manufacturers have affirmed that fuel consumption reductions well in the range of 2% are achievable.

4.2 Further Optimisation Potential

Eliminating the pressure oil supply into the bearing coupled with having a raceway on the shaft itself creates further interesting potential for optimisation. Since the force action of balancer shafts is generated by their imbalance, the force revolves together with the shaft, i.e. the direction of action relative to the shaft does not change. For the rolling bearings, this means that only those rolling elements located on the side of the imbalance mass will ever transfer force from the shaft to the housing, **Figure 8**.

The unstressed rolling elements located in the area opposite the imbalance are kept in contact with the outer race by their centrifugal forces and do not come into contact with the shaft. This eliminates the need for a shaft raceway here. This area is only required to perform a force-supporting function when the engine is switched off and the imbalance mass is directed upwards. However, the forces generated in this condition are so low that a significantly reduced raceway width will suffice. Retaining a certain residual raceway width is also recommended in many applications for acoustic and rolling bearing design reasons.

Reducing the raceway width on only one side will increase the imbalance. In order to restore the target imbalance, mass is removed on the unbalanced side as close as possible to the axis of rotation, as this increases the amount of mass to be removed. The consistent use of these opportunities for optimisation enables a balancer shaft mass that is 20 to 40% lower than that of existing designs. In the case of a four-cylinder engine, this can mean a mass reduction of up to 1 kg. The mass moment of inertia in the balance shafts is also reduced by around the same percentage and this notably affects the design of the drive train from the crankshaft to the balancer shafts. There are also direct benefits for the acoustics of this part of the drive train in the form of reduced excitation. The practical significance of all these benefits has been impressively illustrated in [7].

Based on rolling bearing considerations, the reduction in the raceway width ultimately has rolling bearing-specific benefits. With a cylindrical raceway design and the attempt to eliminate the pressurized oil supply via a supply hole, the possibility of oil mist penetrating the bearing is restricted to a very narrow gap between the race and the outer ring, as in the lower bearing part in **Figure 9**, the new design, however, creates a direct, widespread access for oil mist to the roller set, Figure 9, top part. This therefore significantly expands the application field for rolling bearings with oil mist supply.

5 Conclusion

The use of rolling bearings in modern engines is not new in principle, as demonstrated by the widespread use of full complement needle roller sets in cam followers. It is therefore all the more important to use the potential for reducing friction on the crankshaft, camshaft and balancer shaft bearings, as well as in gear drives and even exhaust gas turbochargers. Considerable application-related secondary effects can also be employed. In many cases, the lower amount of heat generated in the bearings can be dissipated through the surrounding components, which eliminates the need for a pressurized oil supply. Oil supply holes can be omitted and the required amount of pressurized oil in the engine is reduced. The much lower lubrication oil requirement and im-

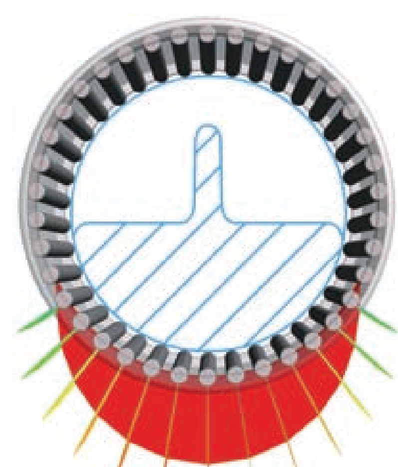

Figure 8: Load distribution in the rolling bearing of a balance shaft

Figure 9: Optimised design of a balance shaft rolling bearing

proved dry running characteristics permit a significantly higher number of start/stop operations. By virtue of their design, the rolling bearings on mass balancer shafts permit a significant reduction in mass and mass moment of inertia. The result is advantages in terms of engine weight, partial drive train design and acoustics. The angular ball bearings employed in gear drives exhibit an increased bearing capacity with regard to tilting torques and reduced clearance, resulting in highly advantageous acoustic behaviour. The overall combination of the advantages described here creates a remarkable cost/benefit ratio for this established technology.

References

[1] Tiemann, Ch.; Kalenborn, M.; Orlowsky, K.; Steffens, Ch.; Bick, W.: Ein effektiver Weg zur Verbrauchsreduktion: Wälzlagerung im Verbrennungsmotor [An effective way of reducing fuel consumption: rolling bearings in the combustion engine] In: MTZ 04/2007 Volume 68, p. 286-293

[2] Schwaderlapp, M.; Dohmen, J.; Haubner, F.: Reibungsminderung – Konstruktive Beiträge zur Kraftstoffeinsparung [Friction reduction – design-based contributions to fuel savings] In: 11. Aachener Kolloquium Fahrzeug- und Motorentechnik 2002 [Aachen colloquium on vehicle and engine technology] p. 909-920

[3] Nadelkränze für Kurbelzapfen und Kolbenbolzen [Needle cages for crank pins and piston bolts] Product leaflet, Schaeffler KG 2007

[4] Pischinger, S.; Sonnen, S.: Erforschung des Geräuscheinflusses von Wälzlagern als Kurbelwellen-Grundlager [Research on the noise influence of rolling bearings as crankshaft main bearings] Final report on the FVV Research Project No. 881, Volume R 541, Informationstagung Motoren [Information conference on engines], Spring 2008, Frankfurt am Main

[5] Krimpmann, M.; Vesselinov, V.; Weber, J.: Numerische und experimentelle Analyse der Kinematik von Rollenlagern [Numerical and experimental analysis of the kinematics of rolling bearings] „Konstruktion“ [Design] 4/2004, p. 59-66

[6] Brändlein, J.: Gestaltung von Gehäusen für Wälzlagerungen – Teil 1 [Design of housings for rolling bearings – Part 1] Antriebstechnik [Drive technology] 34 (1995) No. 9, p. 61-65

[7] Gruber, G.; Prandstötter, M.; Hollnbuchner, R.: Integriertes Ausgleichswellensystem für den Vierzylinder-Dieselmotor von BMW [Integrated balance shaft system for BMW four-cylinder diesel engines] In: MTZ 06/2008 Volume 69, p. 518-524