

Rolling Elements Assessment on Crankshaft Main Bearings of Light Duty Diesel Engine

Yannick Baubet
SKF

Carl Pisani and Phil Carden
Ricardo UK Ltd.

Lex Molenaar and Adam Reedman
SKF

ABSTRACT

Rolling element bearings are known to give reduced friction losses when compared to the hydrodynamic bearings typically used to support the crankshaft in multi-cylinder engines. This paper describes the design, manufacturing and testing of a modified 4 cylinder light duty Diesel production engine with rolling element bearings applied at the crankshaft main bearings in view of CO₂ emission reduction. Selection of the most suitable type of roller bearings for this specific application was made. Technology development through multi-body dynamic simulation and component testing was done to assess the effect on rolling elements performance due to the key challenges inherent to such bearing solution: high instantaneous combustion load, lubrication with low viscosity and contaminated oil, and the cracking process to split the bearing outer raceway.

Compared to the baseline production engine with hydrodynamic bearings, a clear cranktrain friction reduction (–58% at ambient and –30% at 90°C) was measured under motored conditions. Both engines were then subjected to fuel consumption testing on a steady state engine dynamometer test bed under a wide range of operating conditions (speed, load, temperature) which indicated 2% fuel economy on average. Clear fuel economy improvement was demonstrated during the transient warm up phase (first fifteen minutes of operation) and typically 7.5% fuel economy was measured during the first five minutes. The fuel consumption over NEDC was calculated from the measured steady state points and leads to a 1.8% fuel economy compared to the best-in-class Euro6 Diesel engine selected.

Noise and vibration measurements were also made to support the roller bearings assessment. Performance of the rolling element bearings was validated through full load combustion operation along the whole engine power curve. Finally and in view of mechanical development, the roller bearings engine was subjected to continuous operation at the engine's maximum torque with increasing peak firing pressure.

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INTRODUCTION

The UK Technology Strategy Board sponsored the Syner-D project, described by McCartney et al [1], which was initiated in order to assess the feasibility of developing a low cost low CO₂ emission approach, i.e. sufficiently cost effective to be applied across a wide range of vehicles whilst delivering emissions compliant with Euro6 standard.

In addition to the efficiency of gas exchange and combustion, the fuel consumption is significantly influenced by engine friction. Important fuel consumption benefit can be achieved within the engine warm-up phase. As described by Zammit et al [2] and Tiemann et al [3], it is known for passenger car engines that the main bearings of the crankshaft play a significant role in global friction loss and particularly during the warm-up phase. The use of roller bearings instead of conventional journal bearings offers an interesting potential for improvement.

Historically, roller bearings have been applied to low-load areas of engines such as camshafts, and in some applications rolling element crankshaft bearings have been developed, predominantly for gasoline applications, specifically highlighted by Tiemann et al [3]. Hundred years ago, as depicted in SKF general catalogue from that period [4], self-aligning roller bearings (SABB) with gradually decreasing inner diameter were simply shifted on the crankshaft (balancing counterweights were not used at that time).

The technologies and methodologies which were selected within the Syner-D project with the aim to reduce the engine friction, reviewed by McCartney et al [1], include in particular: Diesel engine downsizing, 8-speed automatic transmission in view of downspeeding, intelligent thermal management, advanced lubricants, and roller bearing crankshaft.

For the latter, three classes of technical challenges need to be addressed. The assembly requires to split the bearings and to deal with higher tolerance dispersion compared to roller bearings standard. Lubrication with engine oil, meaning low viscosity, soot contamination and specific additives, is outside roller bearings standard usage. The third challenge is consequently the reliability, typically when considering the high dynamic load coming from the Diesel combustion.

This paper describes the development of the roller bearing crankshaft and the benefits achieved. The objective was to enable a better understanding of the key challenges for this technology through various technical feasibility assessment activities. The selected approach has been through design, modeling & analysis, technology development, engine testing, NVH assessment and mechanical development.

DESIGN, MODELING & ANALYSIS

A modern 2.4L Turbo Diesel DI engine was selected to support the activity. A particular requirement was the crankcase suitability for receiving the roller bearing crankshaft since the outer diameter of the roller main bearings is larger than that of typical hydrodynamic bearings.

An important consideration for this bearing solution development was to maintain it at a cost effective level in comparison to the friction benefit. For this purpose, the bearings system was intended to be applied to the engine without significant change to the base engine design, manufacturing process and tolerance. The final aim was to provide sufficient reliability for the application so that the benefits on fuel and CO₂ will become available for the customers.

Bearing Selection

Main specificities of Diesel engines are the high dynamic load and the induced deformations of the bodies which affect the outer raceway with partition lines and the whole bearing through misalignment between inner and outer raceways.

The prime order parameter to dimension and evaluate roller bearings is the Hertzian pressure at the rolling contacts. Such stress depends principally on the contact characteristics and on the bearing radial load.

To select the most suitable roller bearing type, some simulations were carried out using SKF Bearing Beacon software. Different bearing types were tried within the same radial load and clearance. Figure 1 provides the comparison between the most interesting candidates with line contacts. Standard CRB type with straight line contacts is known to induce edge stress and as a consequence was not preferred at this level for a Diesel application. CARB type is characterized by curved line contacts which remove the edge stress phenomenon. Main specificities of CARB is that its geometry provides some self-alignment capability and the internal design can be adjusted to the application requirements. CARB #1 shown is relatively close to a CRB and CARB #3 shown is closer to a SRB. As a compromise and to deal with misalignments while keeping acceptable load carrying capacity, the CARB #2 has been finally retained for the project.

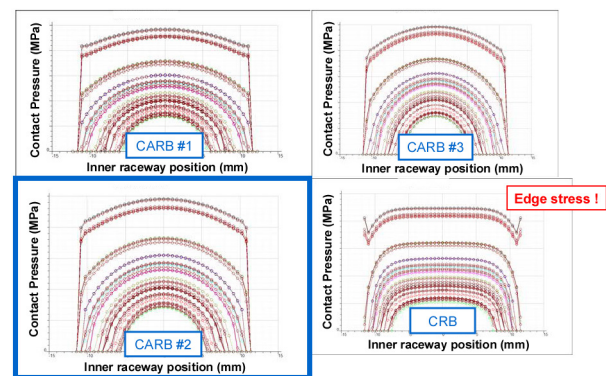


Figure 1. Hertzian pressure of various rolling contacts simulated with SKF Beacon indicating CARB design suitable to avoid edge stress and accommodate shaft bending

Embodiment Design

The bearing solution was designed such that the inner raceway was the actual crankshaft surface hardened with induction and machined to suit the toroidal rolling elements. The oil feed to the connecting rods (journal bearings) was maintained through the crankshaft.

The design used a housing part in which the outer raceway was directly machined. Such a solution offers more flexibility for the integration into the donor engine crankcase.

An oil control system was introduced into the housing to lubricate properly the roller main bearings while directly using the crankcase main oil gallery.

The cage design has been voluntarily put on the safe side to allow proper testing of the rolling contacts within this new application. The solution used for the cage was more representative from Industrial Market than Automotive Market.

The integration of this new CARB solution into the donor Diesel engine is depicted in figure 2. Further details of the rolling element bearing crankshaft are provided by Baubet et al [5].

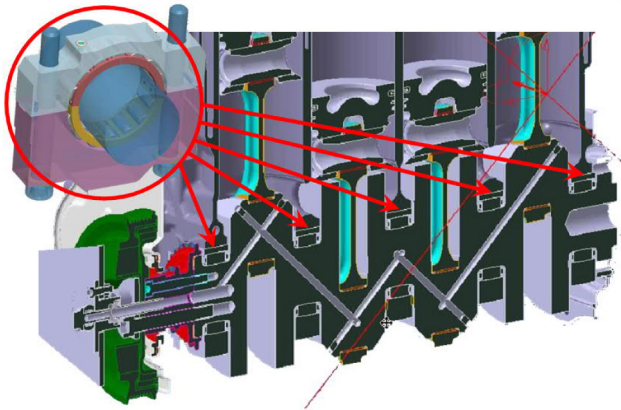


Figure 2. CARB integration into donor Diesel engine at the five main bearing positions named MB1 to MB5

Cranktrain Verification

To confirm the design choices and later to feed more complex simulation needs, some basic simulations of the crankshaft dynamic behavior were carried out. A specific stiffness matrix for each bearing type was taken into account. It allowed the misalignment comparison between journal bearings and roller bearings. Figure 3 shows a comparison between calculated peak relative tilt angles at each main bearing.

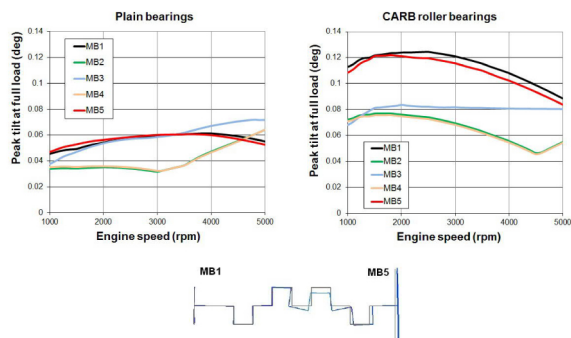


Figure 3. Crankshaft dynamic behavior with bending, introducing misalignment at the main bearings showing increased misalignment at MB1 and MB5 with roller bearings

It is noticeable that, due to the relaxed degree of freedom in rotation inherent to CARB, the global misalignment was increased. Such phenomenon was acceptable since the selected bearing type is tolerant to these misalignments.

The necessary design modification of this specific crankshaft led to a slight reduction of its stiffness which explained the relatively high misalignment values at MB1 and MB5.

Bearing Housing Verification

Simulations were carried out with FEA using Ansys in order to verify the bearing housing design and to study the influence of the main bearing bolt tightening and of the combustion on the outer raceway roundness considering the partition lines.

Extreme conditions occurring during combustion at maximum torque on MB4 and at maximum speed on MB3 in particular during overlap were considered. The design of the housing resulted in acceptable stress according to the selected material fatigue limits.

Specific attention was paid to the interfaces between the housing and the crankcase and between the two parts of the split housing. Figure 4 gives the contact pressures at each interface with the minimum tightening load retained and under the maximum combustion load. Sufficient pressure guaranteed that no separation of these interfaces would occur.

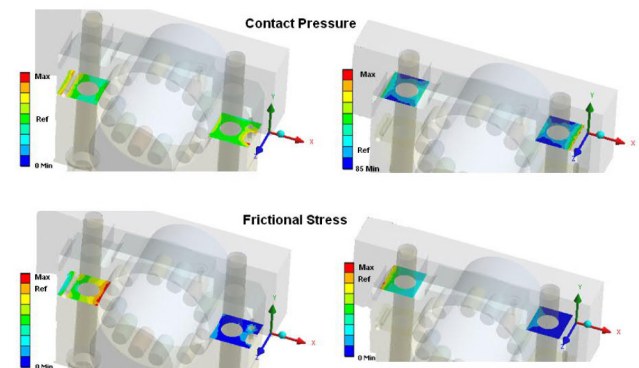


Figure 4. Contact pressure and frictional stress distribution at housing interfaces with combustion load simulated in Ansys showing no separation of the parts

Deformations were investigated under the maximum tightening load. The outer raceway was machined into the housing under clamped conditions so that no residual deformation was expected when re-assembled into the engine. Figure 5 illustrates the impact of the bearing loading condition on the outer raceway roundness. Extreme conditions such as maximum torque combustion for MB4 and maximum speed lateral inertia load for MB3 were studied. Elastic deformation of the housing at the split edge induced a step into the rolling track and this was particularly noticeable at high engine speed where lateral force became high enough. It justified the need to introduce a profile on the split edges to ease rollers transition.

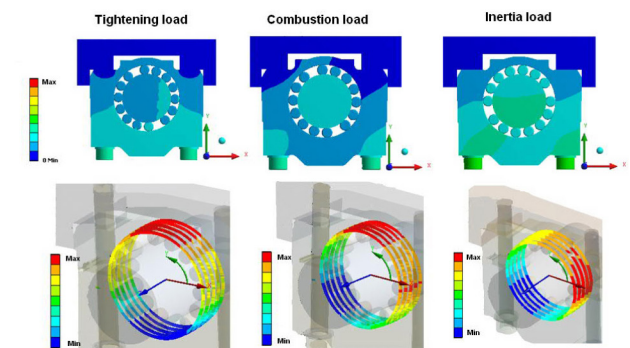


Figure 5. Housing and outer raceway deformations with tightening, combustion and inertia load simulated in Ansys showing step formation at split interfaces

Bearing Internal Dynamics

To develop and verify bearing internal dynamics and build experience from this challenging application, multi-body dynamic simulations were carried out using SKF BEAST software, known for its remarkable accuracy: few percents on both loads and displacements. Flexibility of the housing was set as pre-requisite in order to realistically model the bearing behavior in relation to the crankshaft dynamics (instantaneous misalignment) and to the engine instantaneous combustion load cycle. Both cases, MB4 at maximum torque and MB3 at maximum speed, were analyzed as depicted in [figure 6](#).

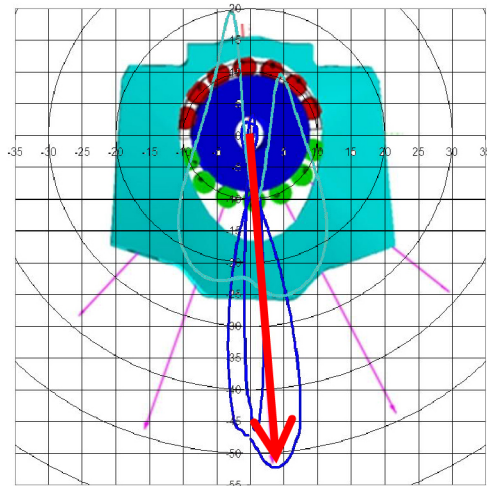


Figure 6. SKF BEAST multi-body dynamic simulations with flexible housing to model the effect of combustion load

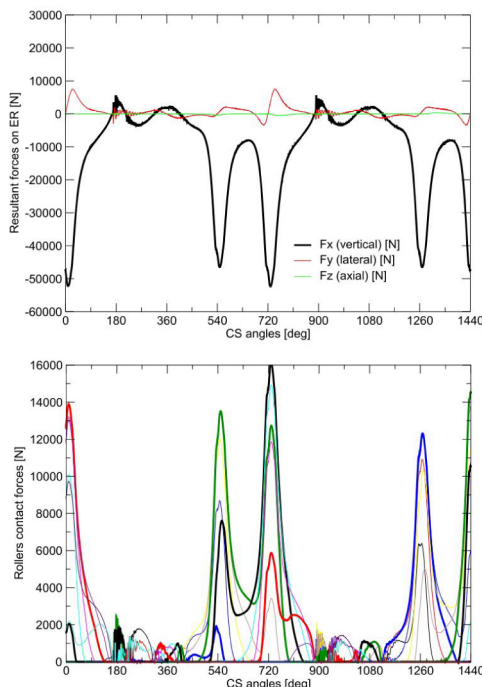


Figure 7. Dynamic bearing and roller loads at maximum torque simulated in SKF BEAST indicating wide loaded zone

[Figure 7](#) shows the main bearing forces and the corresponding load share by the various rollers. A wide loaded zone was seen at the maximum combustion events. Even if instantaneous by nature, the high combustion load was shared between most of the rollers so that locally the Hertzian pressure stayed within acceptable limits.

[Figure 8](#) shows the skew of the rollers (misalignment of the roller rotational axis according to its rolling direction) and the forces transmitted at the interfaces between the cage halves. Relatively high levels of skew have been found since these are directly depending on the bearing misalignment (combustion events). The skew pattern was getting worse and harsh with the speed, so sufficient radial clearance should be provided for this application to ease rollers adjustment to the raceways in particular at inlet and outlet of the loaded zone. It was noticeable that cage interface forces were directly impacted by the rollers skew since the role of the cage is to control the rollers' motion when they are not in the loaded zone.

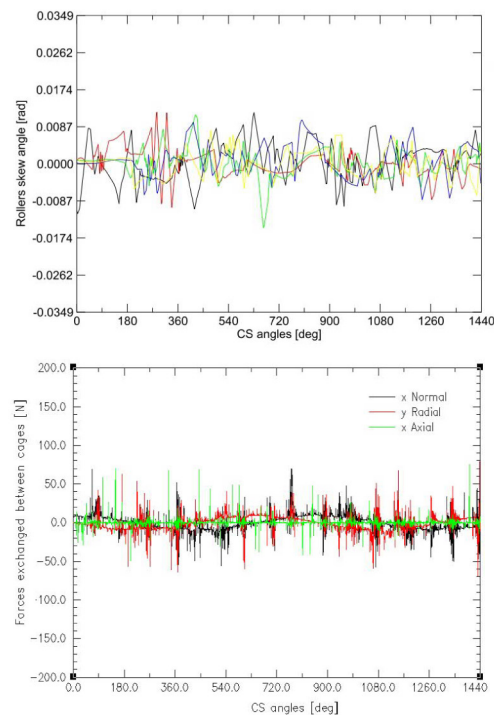


Figure 8. Dynamic roller skews and cage forces at maximum torque simulated in SKF BEAST showing relatively large skew values (suitable for CARB) and acceptable cage forces

Such simulations, considering their low uncertainty level, were used to determine the required bearing radial clearance and to check the cage suitability. Specific consideration of the load building-up at the combustion events and the effect on bearing internal dynamics confirmed the suitability of CARB to this Diesel application.