

Energy Efficiency

BY USING

INNOVATIVE BEARING SOLUTIONS

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Management Summary

Based on simulation methods and calculation tools developed by the Schaeffler Group and presented in the first part of this paper, three approaches regarding increased efficiency based on rolling bearings are presented.

The first approach addresses the overall bearing concept itself. It shows which bearing concept exhibits the highest potential for reducing friction within the customer's system.

The second approach focuses on reducing the friction of the rolling bearing itself. In this respect, optimization of the internal bearing geometry—as well as of the tribological conditions of relevant friction partners (e.g., roller face versus rib)—plays a key role. Examples used here are low-friction, tapered-roller and deep-groove ball bearings.

The third approach facilitates higher efficiency through downsizing. For example, the load-rating capacity of the Schaeffler Group's new ball roller bearings is enhanced by their ability to place a higher number of rolling elements into the bearing without increasing its size.

Introduction

Rolling bearings and saving energy go hand-in-hand. In other words, the original purpose of a rolling bearing is to save energy by reducing the friction between mechanical parts in movement against each other—be it the rotation of a wind turbine, the wheel of a car or the shafts of a transmission. Accordingly, the rolling bearing is a key machine element with respect to the improvement of energy efficiency of a machine or system. In order to meet growing market demands in this field, the Schaeffler Group develops and manufactures low-friction bearing solutions. Schaeffler's engineering expertise in this respect is based on simulation and calculation tools, understanding and analyzing the customer's bearing-related system as a whole, as well as providing appropriate low-friction bearing components.

Analytical Model for Calculating and Minimizing Friction of Rolling Bearings

There are currently two methods for calculating the friction of rolling bearings.

The first approach is to use the catalog method of the rolling bearing manufacturer and the second is to use highly specialized multi-body simulation (MBS) programs. The catalog method involves the use of empirical approaches. They enable the frictional torque to be calculated quickly for low model accuracy. On the other hand, MBS programs such as the *CABA3D* (Ref. 1), developed by the Schaeffler Group, have a very high model accuracy that require longer calculation times.

In order to combine the advantages of the catalog method and the MBS programs, the Schaeffler Group has developed

a new analytical model for calculating rolling bearing friction. This model was implemented in the *BEARINX* (Ref. 2) program so that the new friction calculation is available to a large group of users. Advantages are short calculation times and the consideration of various influencing factors such as real stress distribution and the internal geometry of the bearing. Furthermore, the rolling bearing power loss of entire shaft systems or transmissions can be calculated, as well as load distribution and rating life. Thus it is possible to select an (friction) optimized bearing design, even in the early product development phase.

During this process, *BEARINX* addresses various influencing factors such as the elasticity of the shaft and housing, the contact stresses from non-Hertzian calculation methods and, of course, the internal geometry of the bearing (profiling, osculation, contact angle, etc.). Figure 1 displays an example of a *BEARINX* model of a transmission.

The detailed calculation results and the (internal) bearing geometry are the input variables for the new friction calculation.

Elastohydrodynamic Lubrication

The elastohydrodynamic lubrication (EHL) theory deals with the formation of a lubricant film in the contact points of bodies under high loads when rolling at high speeds (Ref. 3).

The term elastohydrodynamic lubrication involves two phenomena. One, the formation of a hydrodynamic lubricant film, i.e.—the independent build-up of pressure due to the lubricant wedge effect of the flow of a viscous fluid. Two, the elastic deformation of the contact bodies, which, in conjunction with the increase in viscosity of the pressure zone, makes

a significant contribution to the increase in hydrodynamic load-carrying capacity (Ref. 4).

Figure 2 shows the ratios in the EHL contact. Both contact partners undergo elastic deformation during contact. The central lubricant film height h_0 is present in the largest section of the lubrication gap. Contraction occurs on the outgoing side. Here, the lubrication gap is reduced to the minimum lubricant film height h_{\min} .

Figure 2 also shows the adaptive pressure distribution in the EHL contact and the elliptic pressure distribution according to Hertz. The pressure builds up slowly on the incoming side. In the area of the central lubricant film height, the pressure progression almost corresponds to the pressure progression calculated according to Hertz. A sharp increase in pressure occurs on the outgoing side due to the narrowing of the gap.

Frictional Components

The friction in a rolling bearing is made up of several components—rolling and sliding friction and churning losses.

A rolling friction component is the outcome of lubricant compression in the inlet zone of the EHL lubricant film (Fig. 2). A further component of rolling friction is material hysteresis. When the rolling elements roll on the raceway, the areas in front of the rolling element are deformed and the material compresses. When the material is unloaded, only a portion of the energy is used for the rolling motion. The remainder is converted into heat, due to internal material friction.

In general, sliding occurs in all contact points of a rolling bearing; e.g., between rolling element and raceway or cage. This can involve macro slip or micro slip. What is known as a differential slippage always occurs in ball bearings due to the varying distance of the individual contact area points of the axes of rotation of the bearing elements. This means that the center section of the ball surface slides in the opposite direction of the direction of rolling and that the external sections slide in the direction of rotation.

A further sliding friction component is the spinning friction. This is caused by slippage that occurs when a rolling element (a ball in this case) turns on the vertical axis of its contact (Fig. 3).

Churning losses caused by lubricants occur in the bearing along with rolling and sliding friction. These losses are highly dependent on the quantity of oil or grease found in the bearing and adjacent construction, and cannot be analytically calculated according to the state of the art. It is for this reason that we acted on the assumption that the bearings were lubricated with a minimum quantity of oil below.

New Friction Model for BEARINX and Validation

Viscoelastic and nonlinear viscous effects were taken into consideration in the friction model developed for BEARINX.

Each contact must be taken into account individually in order to calculate the collective spinning friction and the influence of differential slippage on the frictional torque of rolling bearings. In turn, the local increase in temperature affects the viscosity and thus the frictional force. This means that the calculation must be iterative at this point. After successful iteration, all frictional forces on the discrete points of the contact surface—as well as the distribution of tempera-

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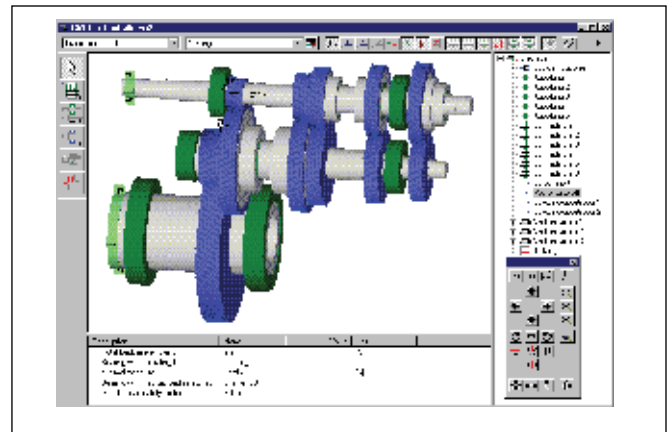


Figure 1—Model of a passenger car manual transmission in BEARINX.

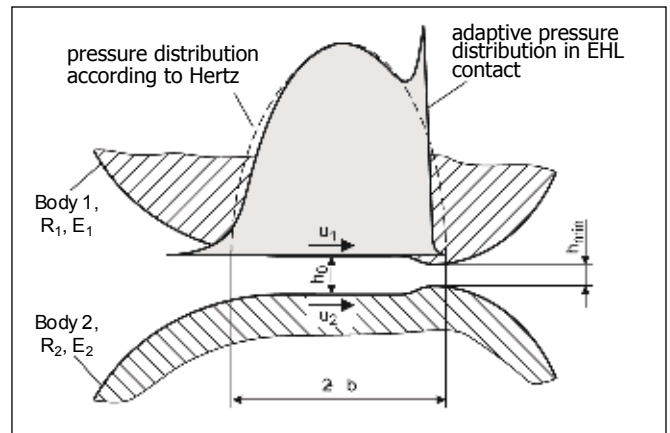


Figure 2—Elastohydrodynamic contact (Ref. 5).

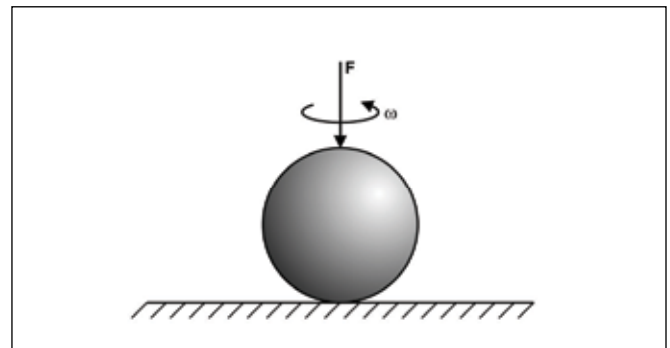


Figure 3—Spinning friction illustrated with ball/plane.

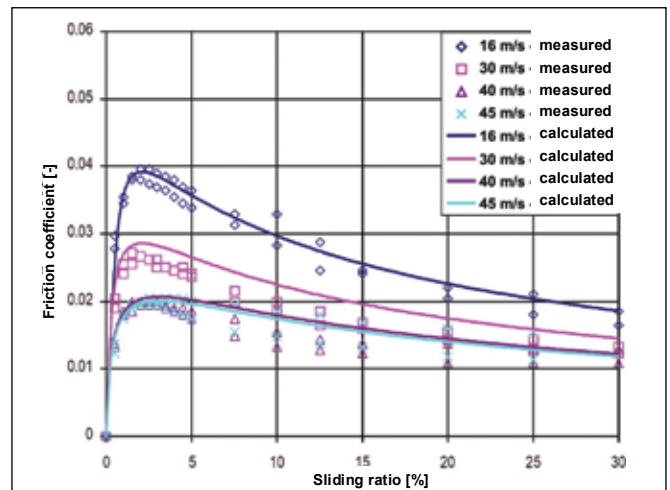


Figure 4—Friction coefficient as a function of slip increase: comparison of measurement and calculation.

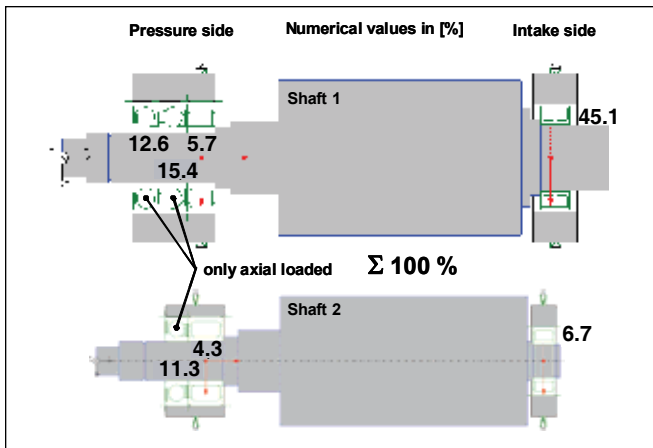


Figure 5—Relative portion of the individual bearings on the total frictional torque of compressor Shafts 1 and 2—initial condition (Authors' Note: pressure side is left; angular contact ball bearings do not carry radial load; all numbers in %).

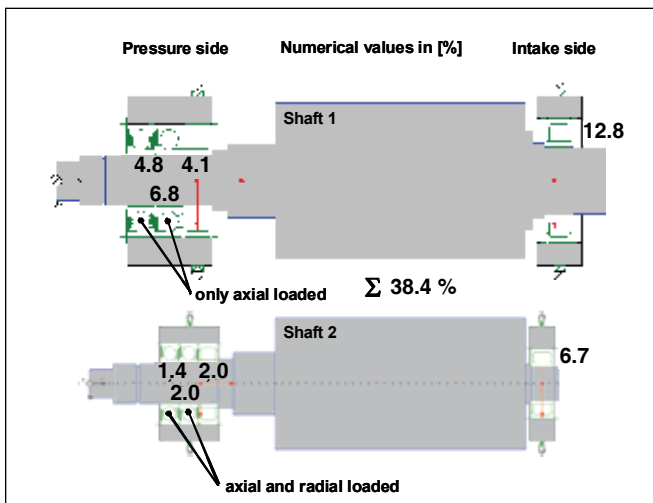


Figure 6—Relative portion of the individual bearings of the total frictional torque of compressor Shafts 1 and 2—variant with optimized friction characteristics.

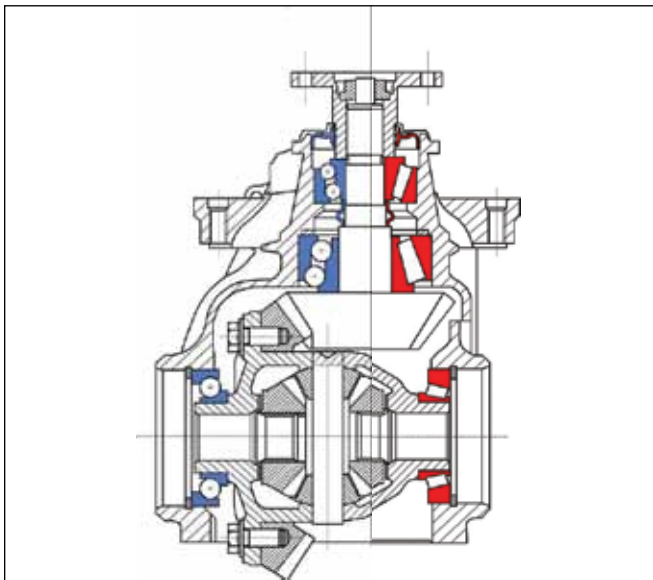


Figure 7—Tandem ball bearing (blue) versus tapered-roller bearing (red) in rear-axial differential transmission.

ture increases—are available in the calculation results.

The redeveloped method for calculating friction with *BEARINX* was comprehensively validated. During the first phase, friction measurements from 2-disc test rigs were used for the validation. Figure 4 shows the coefficient of friction as a function of the slippage for various accumulated speeds. The measurement values are shown as points and the calculated friction values as the continuous line. The decrease in the coefficient of friction is based on thermal effects. The correlation between measurement and calculation can be assessed as very good. This shows that *BEARINX* is capable in principle of calculating the coefficient of friction of a single-defined contact correctly—both qualitatively and quantitatively.

In the final step of the validation, frictional torque values of rolling bearings were calculated with *BEARINX* and compared with measurements. It was shown that the correlation between the frictional torques, calculated using *BEARINX*, and the measurements is significantly greater than the correlation between the frictional torques calculated using the catalog methods of major rolling bearing manufacturers and the measurements (Ref. 6).

Bearing Concept for Customer Applications with Optimized Friction Characteristics

In order to identify the best low-friction solution for the customer, the new *BEARINX* friction calculation enables the assessment of bearing concepts and friction reduction potentials in the early phases of customer product design and development.

The potential provided by the new *BEARINX* friction calculation are shown below by means of a practical example. Figure 5 shows both shafts of a compressor. Shaft 1 is supported on the pressure side by cylindrical roller bearings and two angular contact ball bearings. On the intake side, it is supported by a double-row cylindrical roller bearing in a housing. Both angular contact ball bearings have radial release, which means that they are subjected to axial load only. The radial load is supported by both cylindrical roller bearings. The bearing support of Shaft 2 is designed in the same way. Due to the lower forces, only one angular contact ball bearing has been used and the cylindrical roller bearing on the intake side is a single-row bearing.

The task involves minimizing the bearing friction of the compressor and the boundary conditions regarding rating life, rigidity and space must be met.

To begin, the friction for all bearings in the initial condition shown in Figure 10 is calculated. If the total bearing friction equals 100%, it is possible to determine the relative portion of each bearing of the total frictional torque. This means that it is possible to quickly identify those bearings that have the largest potential for savings. Figure 5 shows that in this case the double-row cylindrical roller bearing and the angular-contact ball bearings together generate 84.3% of the bearing friction.

The first step involves optimizing the bearing selection and arrangement. The double-row cylindrical roller bearing that generates 45.1% of the losses can be replaced by a smaller, single-row cylindrical roller bearing. This means that the required space at this bearing position can be reduced by over 20%. The cylindrical roller bearing on the pressure side

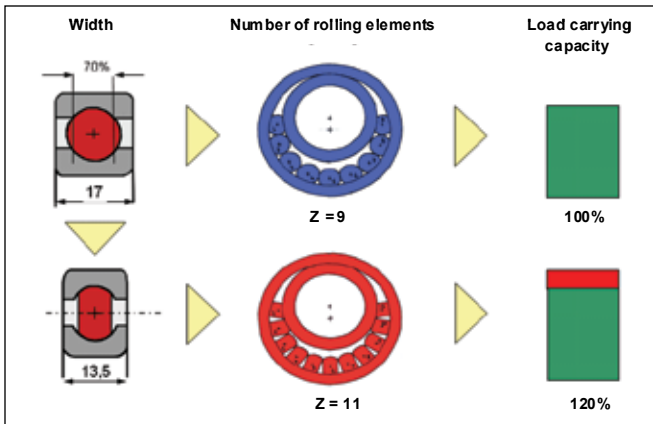


Figure 12—Compared to a deep-groove ball bearing (top), Schaeffler's new ball roller bearing (bottom) is smaller and has a higher load-carrying capacity due to a higher number of rolling elements.



Figure 13—Deep-groove ball bearing 6207 with 9 balls; ball roller bearing BXR 207 with 11 rollers; ball roller bearing BXRE 207 with 14 rollers.

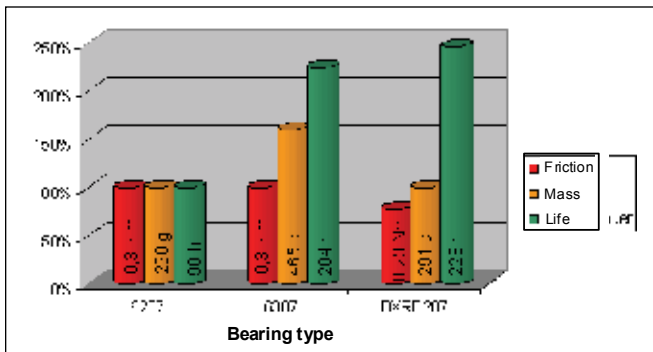


Figure 14—Schematic comparison of friction torque (red), mass (orange) and life (green) of bearing types described in Figure 13 and Table 1—increased power density facilitates downsizing.

Table 1—Load-carrying capacity (dynamic C and static C_0) of ball-roller bearing BXRE 207 compared to deep-groove ball bearing 6207 of same size, as well as to larger deep-groove ball bearings 6208 and 6307 (d , D : inner and outer diameter, w : width).

Type	Size [mm] d/D/w	C [N]	C_0 [N]
6207 BXRE	35/72/17	25.500	15.300
6207	3/72/17	34.500	23.800
6307	35/80/21	33.500	19.000
6208	40/80/18	29.000	18.000

best noise reduction by means of damping.


By developing and applying an improved, high-speed rubber sealing—i.e., HRS—the sealed variant of Generation C deep-groove ball bearings shows excellent friction performance, compared to competitor products (Fig. 11).

Efficiency through Downsizing

This approach facilitates higher efficiency through downsizing. For example, the load-carrying capacity of Schaeffler's new ball roller bearing is increased by the ability to place a higher number of rolling elements into the bearing without increasing its size. This is achieved by slicing the ball on two of its non-load-carrying sides (Figs. 12–13). A “new” type of rolling element is created—a “ball roller.” The resulting higher power density of this ball roller type bearing—i.e., or BXR—is illustrated in Figures 13–14. It enables the customer to select a smaller-size bearing with the same performance, but with significantly reduced friction. Both dynamic and static load-carrying capacity of ball-roller bearing BXRE 207—compared to deep-groove ball bearing 6207 of same size as well as to larger, deep-groove ball bearings 6208 and 6307—are shown in Table 1. For example, if the customer system allows for a smaller shaft diameter, the larger 6208-type can be replaced by the smaller BXRE 207 while increasing load-carrying capacity at the same time.

Conclusion

Rolling bearings and energy savings are symbiotic. The original purpose of a rolling bearing is to save energy by reducing the friction between mechanical parts in movement against each other. Accordingly, the rolling bearing is a key machine element with respect to the improvement of energy efficiency of a machine or system.

It has been proved that the Schaeffler Group can meet growing market demands in this field by establishing benchmarks for calculation tools for customer system analysis and overall bearing concept assessment. In combination with newly developed and qualified low-friction rolling bearings, or Generation C deep-groove ball bearings, it is possible to provide customers a complete low-friction solution. The example of Schaeffler's new ball-roller bearing shows that downsizing is an excellent approach to improving energy efficiency. 

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