How Bearing Design Improves Gearbox Performance

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Gearbox performance, reliability, total cost of ownership (energy cost), overall impact on the environment, and anticipation of additional future regulations are top-of-mind issues in the industry. Optimization of the bearing set can significantly improve gearbox performance.

Introduction

Gearbox efficiency is a topic of rising interest amongst both manufacturers and end-users due to an increased sensitivity to gearbox performance, reliability, total cost of ownership (in relation to energy cost), overall impact on the environment, and also anticipating future regulations.

A gearbox is by nature a quite efficient asset and as such, it has not been subjected to the same debate regarding energy efficiency as other machine components, such as electrical motors. However, due to the increased awareness of environmental impact and the increased energy costs, the optimization of energy is becoming a topic of greater importance also for industrial gearboxes. Looking at the high power/torque transferred by the system, it is of interest to minimize the losses in terms of absolute values (1 percent of 1 MW is still 10 kW). This is especially valid, when existing technology allows it at reasonable cost and without adding complexity.

As there is a competitive advantage to give the maximum possible output mechanical torque in a given gear unit size, there will be a growing competitive race for manufacturers to show the highest thermal rating for a given size (Figure 1). Energy efficiency is increasing its importance among selection criteria.

In this paper, the author will give:

- Recap of gearbox inefficiency sources
- Overview of latest bearing friction model
- Information on latest tapered bearing technology
- How this can affect gearbox performance via single-stage gearbox example

Gearbox Efficiency, Inefficiency and Thermal Rating

As most technicians and engineers learn at school, a gearbox is by its nature an efficient asset. A parallel shaft gear unit typically experiences losses of just 1–2 percent per stage (Ref. 1). Example: a single-stage gearbox could have a nominal efficiency of 98–99 percent.

The losses are of different types/sources:

- Gear losses
- Lubrication losses
- Seal (when present) losses
- Windage losses (high-speed gears)
- Bearing losses

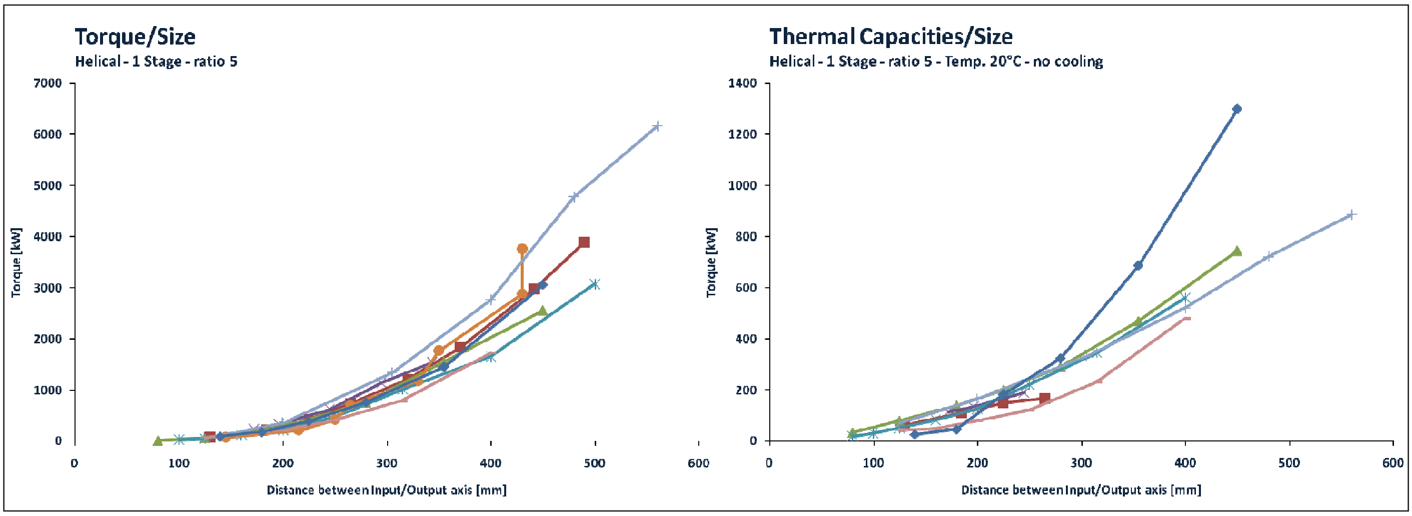

Figure 1 **Mechanical and thermal power ratings of single-stage helical gear ratio 5 for various sizes and gearbox manufacturers.**

Many authors have already described some of these losses and the overall behavior of the gearbox (Refs. 1–3). Those authors showed also that the problem is quite complex, especially because a gearbox is a system where losses interact/influence each other due to the thermal equilibrium/heat dissipation.

An ISO technical report (Ref. 4) published a decade ago lists guidelines for calculating the gearbox thermal rating, which is another term to describe efficiency. The advantage of this rating is that it can be compared with the mechanical rating of the gearbox, and thus the user can quickly see when either a cooling solution needs to be added or improved, or the gearbox size needs to be altered.

Most people believe that the gear losses are the dominating ones. While this is true in many cases, it depends on the gearbox design and load cases (Refs. 2–3). With today's sophisticated engineering software, detailed gearbox analysis has become much simpler, faster and accurate than before; it can help designers (and users) optimize and better understand their system. In doing so, they will learn that the relative importance of different losses can vary significantly, and that losses other than gear losses cannot be neglected in the analysis.

As an example, the author's studies have shown that bearing loss can range from 30–50 percent of the total losses — or nearly equal to the gear losses — depending on the applied loading. When a gearbox is used at the level of its nominal mechanical rating, gear losses tend to be dominant, which is expected.

It is also interesting to note that the split between the different shafts is not equal. Depending on gearbox design, the gearbox ratio, bearing load and speed will vary. As illustrated in Figure 2, one may find cases where the input shaft positions are a major source of bearing loss; others, where the output and intermediate positions are the ones generating the highest bearing losses.

In order to optimize the relevant part of the gearbox, it is therefore important to use and understand the latest knowledge and models regarding bearing friction.

SKF Friction Model

In 2003 SKF published a new bearing friction model in its general catalogue (Ref. 5), (Table 1). This model is based on four sources of friction:

$$M = M_{rr} + M_{sl} + M_{seal} + M_{drag} \quad (1)$$

where

M is total frictional moment, N-mm.
M_{rr} is rolling frictional moment, N-mm.
M_{sl} is sliding frictional moment, N-mm.
M_{seal} is frictional moment of the seal (s), N-mm.
M_{drag} is frictional moment of drag losses, churning, splashing, etc., N-mm.

This new approach (Ref. 6) identifies the sources of friction in every contact occurring in the bearing and combines them. In addition, the seal contribution and additional external sources can be added as required to predict the overall

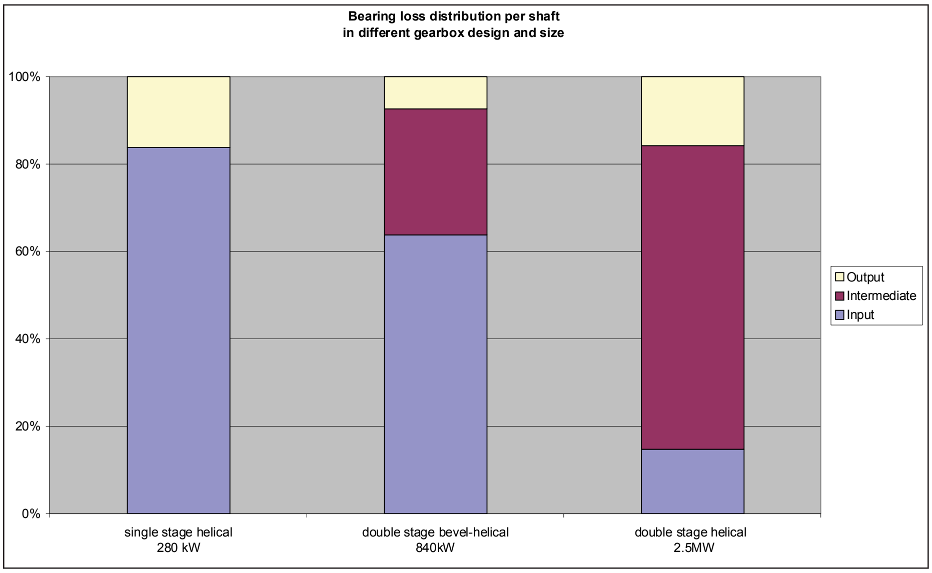

Figure 2 Examples of possible distribution of bearing loss per shaft in different gearbox setup (per SKF investigations).

Table 1 Comparison of philosophy: previous model load-depend/load independent, and new SKF model — four sources of friction

Old model		New model	
$M_b = M_0 + M_1 + M_2 + M_3$		$M = M_{rr} + M_{sl} + M_{drag} + M_{seal}$	
$M_0 = 10^{-7} f_0 (vn)^{2/3} d_m^3$	Load-independent part (mainly rolling)	M_{rr}	rolling friction moment (raceways)
$M_1 = f_1 P_1^a d_m^b$	Load-dependent part (sliding correction)	M_{sl}	sliding and spinning friction moment (flanges, raceways)
$M_2 = f_2 F_a d_m$	RB axially loaded (sliding flanges)	M_{drag}	oil bath, large bath
$M_3 = \left(\frac{d+D}{f_3}\right)^2 + f_4$	Sealed bearings	M_{seal}	friction moment due to seal

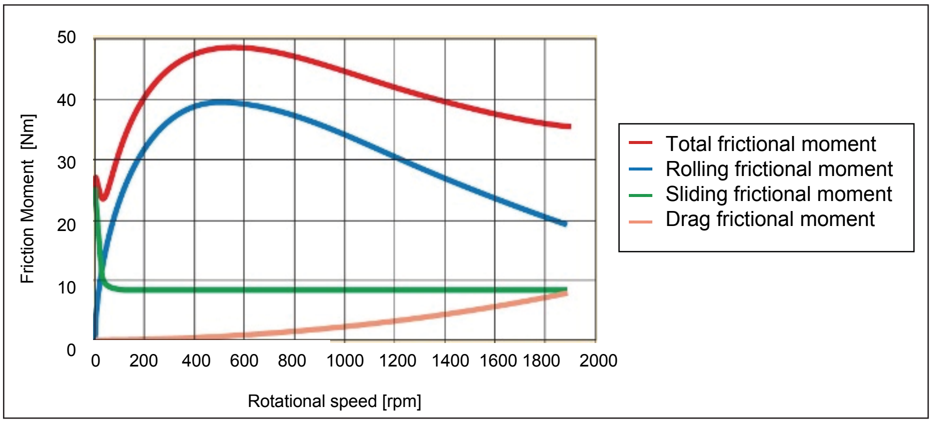

Figure 3 Example of four sources of distribution in a spherical roller bearing with oil bath and thick oil.

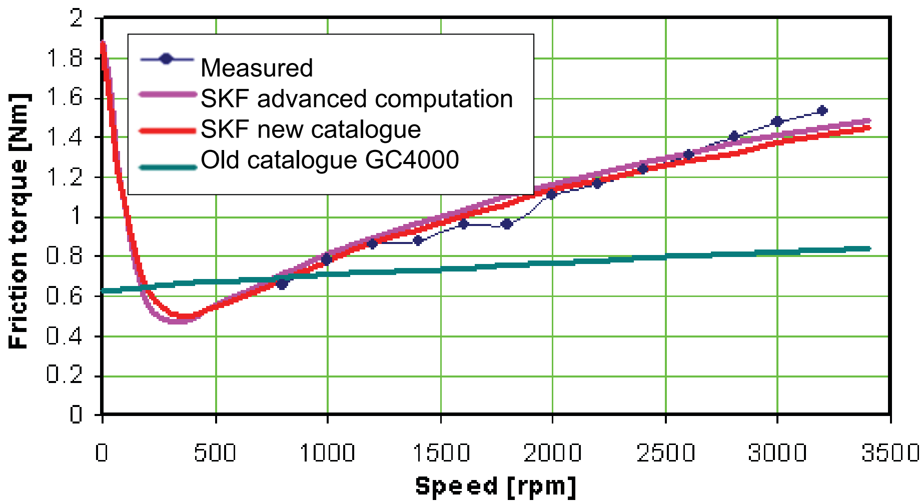

Figure 4 **Model prediction and measurement—tapered roller bearing.**

Figure 5 **SKF energy-efficient tapered roller bearing.**

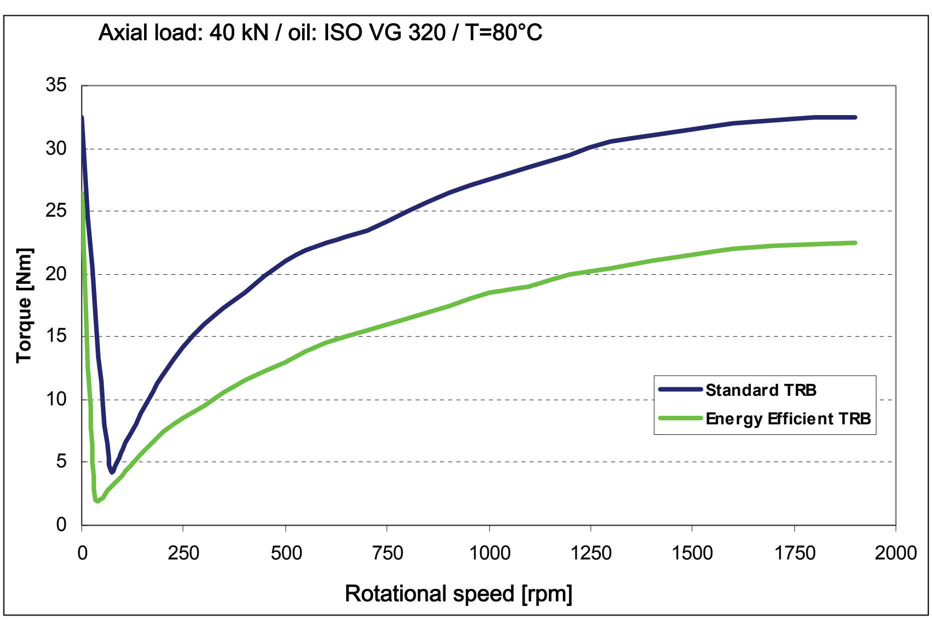

Figure 6 **Frictional moment of SKF energy-efficient tapered bearing vs. SKF standard design.**

frictional moment. Since the model looks into every single contact (raceways and flanges), changes of design and surface improvements can readily be taken into consideration, rendering the model better able to reflect improvement in SKF bearing designs.

This four-source model allows the designer to understand in detail the conditions under which the bearing functions internally. For example, in Figure 3 the four sources of loss are plotted as a function of speed; it can be checked where the bearing losses are driven by rolling or sliding sources.

In addition, Figure 4 shows that the new friction model accommodates bearing friction measurement (here on tapered roller bearing) over the speed range.

Using this new model will allow gear user and designer to make better predictions and provide a better understanding of the bearing losses in a gear unit over various loading conditions. Thus, it allows improved optimization of the system by providing a more accurate comparison between different bearing types and designs.

Energy-Efficient Tapered Bearings

With this improved understanding of friction behavior and a better friction model, SKF was able to develop a new generation of tapered roller bearing (Ref. 7), (Fig. 5), or energy-efficient bearing. These bearings generate 30 percent less friction than conventional tapered roller bearing designs in most loading conditions (Figs. 6 and 7).

Many bearing design parameters were reviewed and optimized to realize this friction saving, and without compromising the fatigue life of the bearing. For example, the new design has some specific flange geometry, reduced recess and extended inner ring raceway. Moreover, special raceway profiles and roller topographies in conjunction with reduced roughness of the ring raceways and flange have been adopted. A special cage with reduced bore diameter—preferably made of PEEK or, for special demands, sheet steel—has been developed.

The most visible change was a reduction in the number of taper rollers. For bearing type 32230 J2, the roller set has been reduced by four. With the reduced number of rollers, the rotating mass decreased by approximately 10 percent.

The reduced number of rollers also has a major influence on lubrication. Fewer rollers mean less friction and mechanical working in the lubricant. This leads to lower operating temperatures, which in turn improves the separation of the surfaces in rolling contact through better lubricant film formation, and this extends lubricant life.

Thirty percent less friction is a quantifiable improvement, but the question for a gearbox designer and user is this: What does it imply for the gearbox performance, in terms of thermal rating and life performance? In the next section, a simulation example of a gear unit is given.

Impact on Gearbox via Single-Stage Gearbox Example

A single-stage helical gearbox was selected for the analysis. This gearbox has a mechanical power of 280 kW and a thermal rating of about 50 kW. The reduction ratio is four. This gearbox is equipped with four identical tapered roller bearings (bore diameter 60 mm, series 323). Bearings 1 and 2 are located face to face on the input shaft; bearings 3 and 4 are located face to face on the output shaft.

The analysis was performed in two steps:

1. A preliminary analysis in which bearing losses and temperatures are calculated based on gear loads and speed effects (no other loss interaction).
2. A complete analysis in which all losses are taken into account — gears, bearings, oil splash.

Both analyses consider the preload/clearance case of the bearings, as it has an important role on the bearing friction itself.

Preliminary analysis. In this first step, the impact of the new bearing design was evaluated only by taking into account bearing-generated heat, and not the heat equilibrium from other losses. This first analysis is very quick and easy to perform and allows one to understand the bearing behavior trends without external influences. It also provides an approximate indication of the loss split per shaft and potential impact of a bearing design change. In any case, it will not yield an accurate prediction of the real perfor-

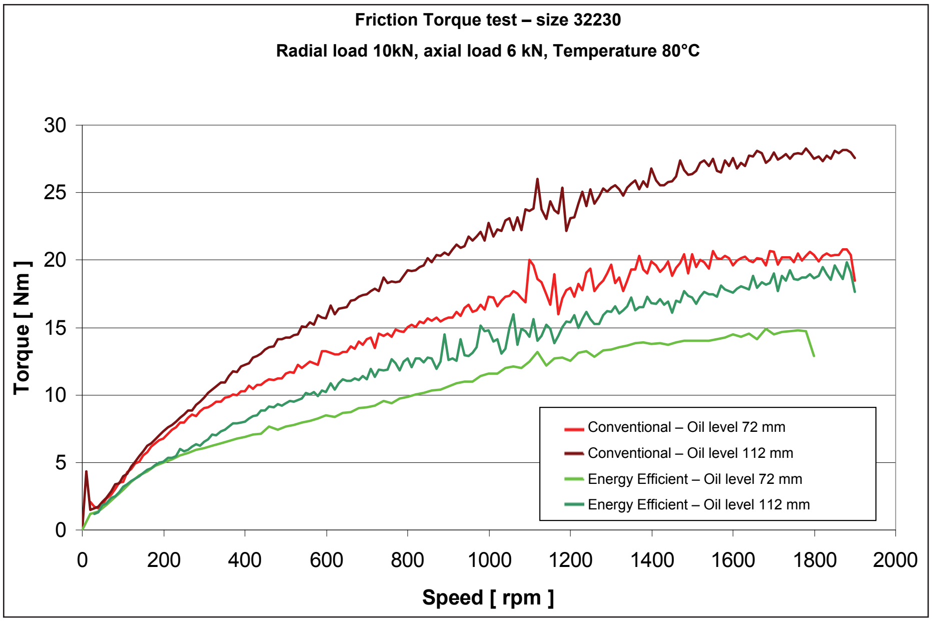

Figure 7 Frictional moment of SKF energy-efficient tapered bearing vs. SKF standard design — different oil level.

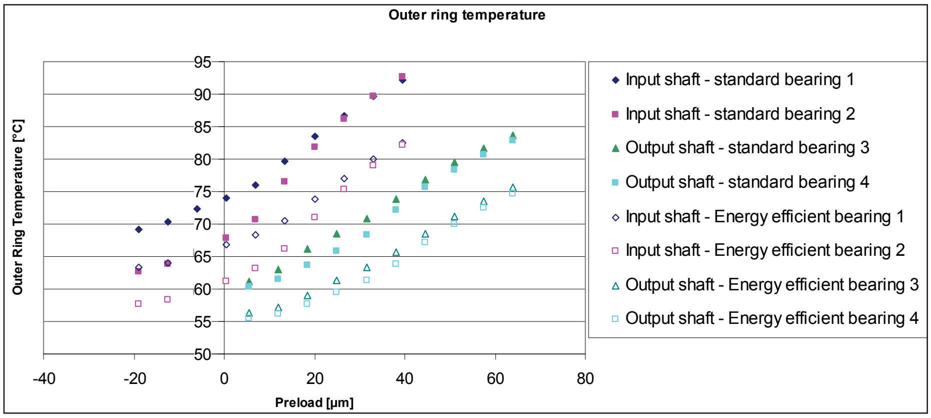

Figure 8 Detailed comparison of outer rings temperature — energy-efficient vs. standard — dependent on preload (bearing losses only).

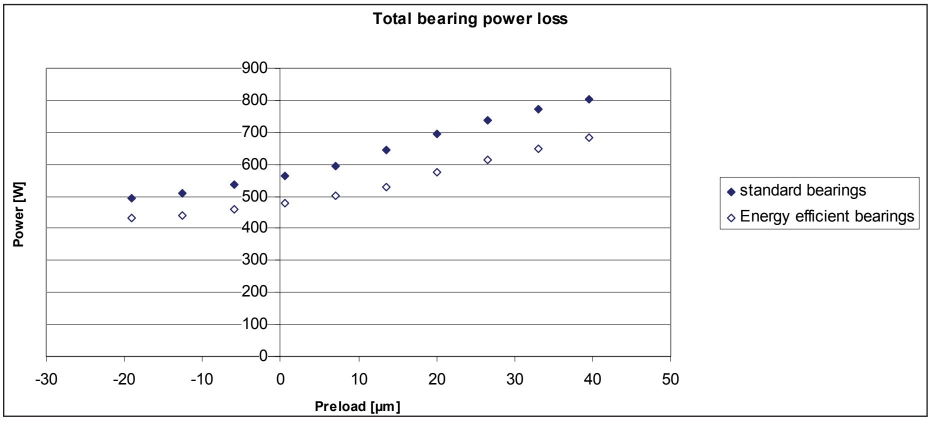

Figure 9 Comparison of the sum of the bearing losses — energy-efficient vs. standard — over the preload range (bearing losses only).

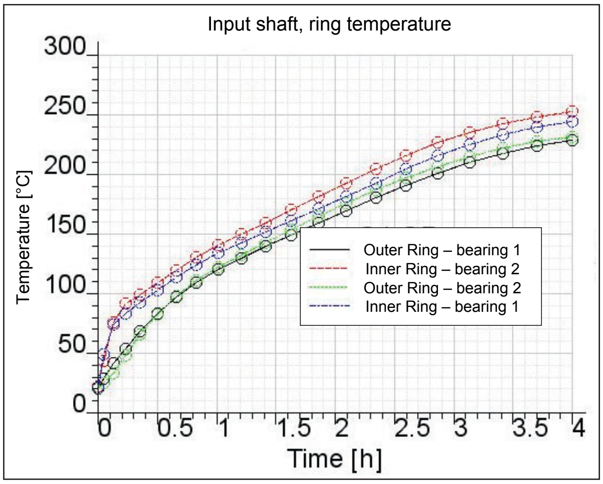

Figure 10 **Loss distribution in gearbox dependent on applied torque — standard bearings.**

Table 2 Average loss and temperature saving — energy-efficient vs. standard		
Loss source	**Standard [W]**	**E2 [W]**
Gear	296	296
Bearing	540	435
Oil splash	156	156
Total	992	887
=> Average saving	10°C and 75W	

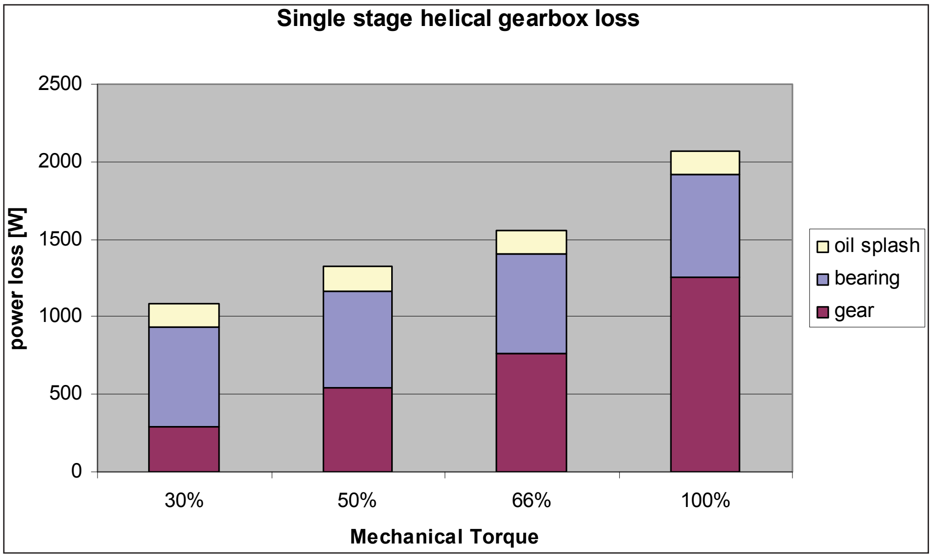

Figure 11 **Transient temperature simulation results — at full mechanical load — for input shaft bearing rings.**

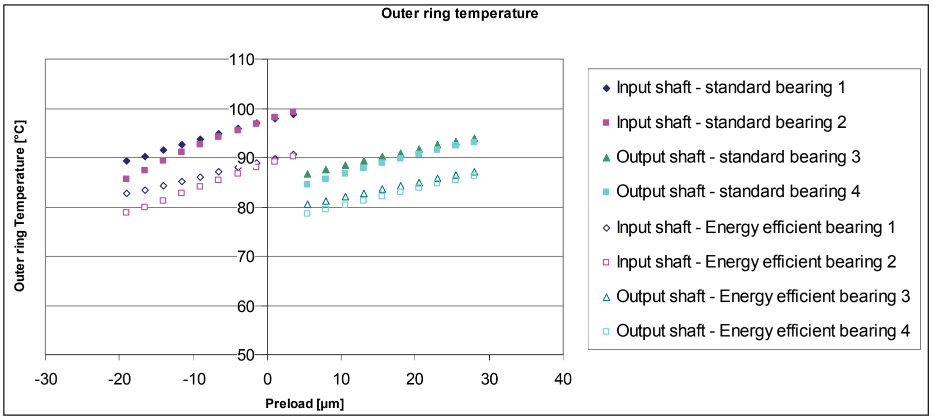

Figure 12 **Detailed comparison of outer rings temperature — energy-efficient vs. standard — dependent on preload.**

mance, as one doesn't take into account the overall heat equilibrium; such results would be more optimistic than the reality.

The detailed results are presented in Figures 8 and 9; the preload effect is very clear on each shaft.

On average — and in comparison with the standard bearing type — the SKF energy-efficient tapered roller bearing design will:

- Save 60–120 watts (power losses reduced by 13–15 percent).
- Run 4–10°C cooler (each position runs cooler).
- Have a longer fatigue life in most cases, due to better lubrication conditions (higher Kappa): min life L10mn >100,000 hrs (following SKF rating life method).

This first analysis indicates good trends: the 30 percent less friction achieved with the energy-efficient bearing is converted into reduced outer ring temperature and reduced friction when applied in the gearbox. Next to analyze is what it means when taking into account the complete system equilibrium.

Complete analysis: The complete analysis was performed including:

- Gear losses according to ISO TR 14179 formulas.
- Bearing losses according to SKF advanced friction modeling tool.
- Oil splash loss according to ISO TR 14179 formulas.

The full gearbox was modeled into the SKF *Orpheus* tool (including the housing). The results analyzed were bearing friction, temperature on the bearing outer ring and bearing life.

As discussed previously, it is interesting to note that gear loss becomes dominant in the highest load case studied. Below 66 percent full torque, bearing and oil splash represent still close to 60 percent of the loss (Fig. 10).

It must also be noted that the gearbox is subjected to forced cooling when power exceeds 30 percent of the nominal load. SKF thermal simulation confirmed that cooling was needed in such a case. Transient simulation showed that heat can increase to unrealistic values if cooling is not applied; at 100 percent load without cooling the heat generated is so high that the simulation would predict a calculated temperature >250°C (Fig. 11). The housing thermal expansion leads to additional bearing load (dependent on grounding). Under the calculated assumption, 10–20 kN additional axial load is generated.

Returning to the main study, the load range of interest is close to 30 percent nominal mechanical power, where the gearbox does not need cooling. In this load condition, one can really measure the impact of a new performance class of bearing (Table 2).

In comparison to the standard bearing type, the energy-efficient tapered roller bearing design:

- Saves 90 to 100 watts (power losses reduced by 20 percent).
- Runs 7°C cooler (each position runs 5 to 9°C cooler on the outer ring).
- Has a similar or higher fatigue life in all cases, due to better lubrication conditions (higher Kappa); i.e., min life > 60,000 hrs

Looking further (Figs. 12 and 13), one can see that the energy-efficient bearings generate lower friction and temperature under the same load, as compared to standard design, whatever the preload/clearance.

Bottom line, without major modification, the performance of the gear unit is increased.

One interesting question is to convert this improved performance (reduced friction and reduced temperature) into a higher gearbox thermal rating: How much more power can this gearbox carry with the energy-efficient bearings, keeping all other parameters (losses and heat) at equal level?

According to the presented calculations (Fig. 14), the thermal rating could be increased by 30 percent when using energy-efficient tapered roller bearings. The new thermal rating can be 70 kW instead of 55 kW.

Conclusion

It has been demonstrated that the contribution of bearing losses to system efficiency is dependent on the load cases. Even if the bearing is not the primary source of losses, optimization of the bearing set can significantly improve the gearbox performance. The simulation of a single- stage gearbox — with tapered roller bearings — demonstrated that the running temperature of the gearbox can be reduced up to 10°C by using newest-technology bearings. Such a saving can improve the thermal rating of the gearbox by up to 30 percent.

Using a proper bearing design can significantly improve the performance of a gear unit by virtue of lower running temperature, improved lubricant life, a potentially simplified lubrication system and inherently reduced running cost.

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Armel Doyer is a mechanical engineer graduated from Technical University of Compiegne (UTC), France in 1999. He joined SKF's development department for deep-groove ball bearings in 2000. Doyer has held various positions within the development department, working predominantly with automotive and industrial applications and contributing to the introduction of the company's energy-efficient bearings. Since 2008 he has been worked as a business engineer within SKF's industrial drive organization, focusing on bearing development for the industrial gear unit market. Doyer is also a member of the AGMA Energy Efficiency Committee.

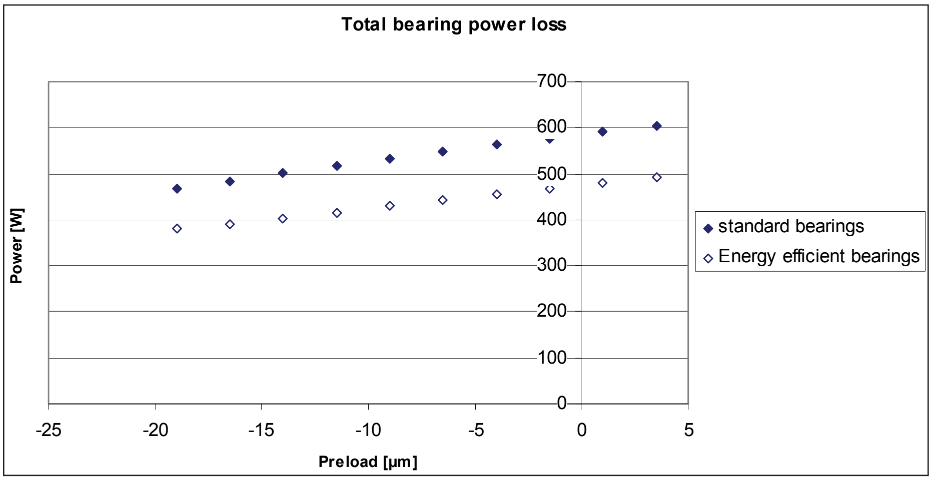

Figure 13 Comparison of sum bearing losses — energy-efficient vs. standard — over preload range.

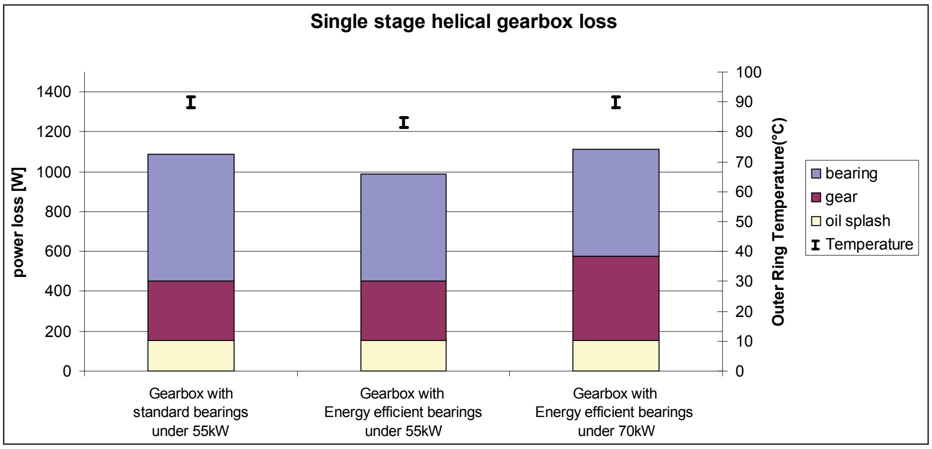

Figure 14 Comparison of total losses and outer ring temperature — standard or energy-efficient bearings — allowing a thermal rating increase.