## **Is Low Friction Efficient?**

### Assessment of Bearing Concepts During the Design Phase

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#### Abstract

Energy efficiency has been a key issue for screw machines for many years. This article describes a new analytical procedure for determining rolling bearing friction and the use of the procedure for designing compressor bearing supports. Further analytical options for a calculative assessment of the overall efficiency of bearing support alternatives are presented in the design phase based on parameter analyses performed by the BearinX<sup>®</sup> calculation software, which includes the new friction calculation by means of a mechanical, tribological model.

#### 1. State of the Art, Determining Bearing Friction Empirically

Energy efficiency has been a key issue for screw machines for many years. Operating and energy costs make up a considerable percentage of the total cost of ownership (TCO) and therefore are increasingly coming to the fore for operators.

In addition to intelligent control and drive technology, many compressor manufacturers are working intensely to increase the efficiency of the screw group itself. An optimized rotor and gearbox bearing support offers good savings potential.

Primarily rolling bearings in a great variety of bearing designs and arrangements are being used to provide bearing support in screw machines.

Previously, the selection of bearings was mainly determined according to the following aspects:

Reliability and long operating life Available installation space, bearing rigidity Ease of assembly Bearing cost and availability Experience from existing solutions Established and internationally standardized calculation methods for bearing operating life (ISO 281) are on hand for optimizations designed to increase productivity.

To date, it has not been possible to sufficiently assess friction and power loss due to relatively imprecise calculation formulas.

Bearing manufacturers offer empirical calculation models that enable calculative estimations based on the load, speed, and operating viscosity of the lubricant and bearing design.

The formulas are based on research by Palmgren in 1957. They were derived from measuring results in tests with laboratory test stands. However, they provide approximations of the measuring results and are only sufficiently precise in narrow ranges. The friction calculation of individual bearing arrangements for specific operating conditions is therefore only possible on a very rough scale.



Fig. 1: Empirical method for calculating bearing friction [1]

#### 2. Determining Bearing Support Friction Analytically

In contrast to the empirical determining process, an analytical calculation begins with a mechanical, tribological model of a rolling bearing.

The mechanical model serves to precisely map force application, load distribution in the bearing, shaft deflection and skew position, operating clearance, the internal bearing structure, and more.

The linked tribological model describes the behavior of the different tribological phenomena. Figure 2 shows the most important friction components of a rolling bearing.



Fig. 2: Friction types in rolling bearings

Unlike with the empirical method, factoring in these friction components results in the addition of fundamental parameters such as those shown in Figure 3.



Fig. 3: Rolling bearing friction, influencing parameters

The BearinX<sup>®</sup> calculation software uses this kind of mechanical, tribological model to calculate the friction of rolling bearing supports. While BearinX<sup>®</sup> is a quasi-static model that offers fast calculation times and high accuracy, a dynamic simulation with the CABA3D calculation software provides enhanced analysis possibilities with additional consideration of cage friction, rolling element contact, and rolling element skewing. A comparison of the calculated friction coefficients and those measured in the test confirms a high degree of conformity and thus the quality of the procedure developed (Fig. 4).



Fig. 4: Comparison of the measured and calculated friction torque force

Figure 4 clearly shows that the empirical method according to Palmgren only provides realistic friction coefficients in a narrow range (approx. 1 to 5 kN here). However, the friction calculated using Bearin $X^{\text{®}}$  is so precise that it lies within the measuring value spread established in the test (0.5 to 15 kN).

#### 3. Extended Application Analyses

The calculation procedure integrated into the BearinX<sup>®</sup> bearing design program offers a powerful tool for the individual modeling and analysis of bearing supports.

BearinX<sup>®</sup> makes it possible to calculate individual bearings and also to model shaft systems and gearboxes while allowing for elastic shaft systems. For instance, in the process, it is possible to investigate details of the individual rolling contact, lubricant film formation, bearing rigidity, shifting, rigidity in the operating points, and even the dynamic analysis of natural vibration behavior (Fig. 5).



Fig. 5: Modular calculation with BearinX®

So-called parameter analyses can be compiled for calculation models. To do this, a userdefined number of model input parameters is given with an initial value and a final value. The program then calculates independently specified output parameters and graphs their change as a function of the input parameters.

For example, a typical analysis would be the operating clearance of a bearing as a function of component temperature with the specified shaft and housing materials/seats and bearing play class.

In the design phase, these parameter analyses are used to investigate the parameters' effects on the command variables being analyzed.

It becomes clear in the process which parameters have the greatest effect. They can then be systematically altered so that they change the overall system behavior in the desired direction.

This frequently makes it possible to avoid or at least reduce complicated, expensive, and time-consuming tests.

#### **Bearing Friction Analysis:**

At the outset of friction analysis, it is interesting to see what kinds of friction the various types of bearings produce.

For instance, the bearing friction analysis for various types of bearings as a function of the induced force as shown in Fig. 6 is helpful in this respect. Instead of individual bearings, bearing combinations were selected for this, of the kind frequently used on the pressure side in screw compressors.



#### Fig. 6: Bearing friction depending on the load

The profiles confirm the known friction behavior of the various bearing types. Here, tapered roller bearings generate the greatest friction forces, whereas angular contact ball bearings and four point contact bearings exhibit considerably lower levels of friction.

#### **Bearing Rigidity:**

The radial and axial bearing rigidity also represent important parameters.

The following figure shows the axial shift of the various alternatives as a function of the axial bearing load.

The greatest axial rigidity levels for the tapered roller bearing support are given here. The ball bearing solutions exhibit lower levels of rigidity.



Fig. 7: Parameter analysis of the axial rigidity

The radial rigidity depends on the type and size of the bearing as well as on the radial bearing play. Figure 8 indicates the radial rigidity of an NU308-JP cylindrical roller bearing.

The radial bearing play has been reduced here between CN, C3, and C2 in stages. The graph shows that the bearing spring deflection can be reduced by restricting the operating clearance. It is necessary to conduct a temperature analysis, particularly in the case of

restricted operating clearance, to prevent inadmissibly high bearing preload levels due to thermal expansion.



Fig. 8: Parameter analysis of the radial rigidity

#### **Bearing Kinematics at High Speeds**

For high-speed screw machines such as oil-free compressors, it is essential to factor in the bearing kinematics in addition to questions of clearance and operating life.

The speed coefficients (nxdm) typically range between 600,000 mm/min. and 1.5 million mm/min.

Centrifugal forces result in unfavorable spin/roll conditions that produce large sliding movements. In favorable lubrication conditions, these sliding movements lead to increased frictional heat or, in mixed friction conditions, to increased fretting. The frictional heat produced must be conveyed away from the contact through respectively high quantities of oil. These oil quantities, in turn, lead to increased churning losses, which once again reduce efficiency. Suitable measures must be adopted to guarantee a minimum bearing load for all operating conditions to avoid negative circumstances and ensure a sufficient operating life.

Parameter analyses of the specific model make it possible to very accurately predict the conditions at which the bearing kinematics will begin to be adversely affected.

Figure 9 below shows that the current bearing configuration exhibits considerable spin/roll effects as of approx. 10,000 rpm, corresponding to a speed coefficient (nxdm) of approx. 435,000 mm/min.

These effects may be reduced to admissible levels by increasing the axial preload accordingly or by using ceramic balls, for example.



Fig. 9: Parameter analysis of the spin/roll ratio

The use of range springs in the calculation model serves to identify shifting at any position in the model.

For instance, this makes it possible to analyze in detail the effect of centrifugal force on the axial skew of the face surfaces with angular contact ball bearings, as shown in Figure 10. Not taking this into due consideration can lead to rotor/housing contact at high speeds.



Fig. 10: Parameter analysis of axial rotor position depending on the rotor speed

#### 3. Example of Optimizing a Gearbox Bearing Support

Even if bearing friction is only slight compared to the overall power loss of a compressor, this is the only analysis option that offers good optimization potential in and of itself.

Upstream gearbox optimization in an oil-injected compressor is presented by way of example. Schaeffler was contacted by CompAir Drucklufttechnik to support the redesign of an oil-injected screw compressor. Figure 11 below shows the initial situation.



Fig. 11: Initial situation for compressor gear optimization

Of the designated load cases, the one with the largest friction loss is selected for optimization (Fig. 12).



Fig. 12: Load case and the BearinX<sup>®</sup> model

After setting up the bearing model in BearinX<sup>®</sup>, comparative bearing models are set up and calculated based on the original bearing support.

The objective is to find solutions with more favorable friction levels and thereby attain operating life values comparable to those of the old solution in order to achieve the same dependability with the new bearing support (Fig. 13).

Screw Machines 2014; Is low friction efficient? SCHAEFFLER Analytical friction analysis; optimization compressor gear input side output side total friction Lh10 N\_R\_L N\_R\_L\_r axial radial Lh10 radial Lh10 N\_R\_L friction compressor portion bearing Axial Radial Radial bearing bearing rad losses bearing \_ax ad power W W W W KW h h % h 279 30219-A 92873 1120 30311-A 76770 446 1566 0,56% QJ214 NU214 590659 118687 84,74 170 NU211 51787 96 351 279 0,13% 7214-B NJ214 924186 208279 81,72 180 NU211 51584 96 358 279 0,13% 58,47 7212-B NJ212 554884 78152 119 NU212 91247 109 286 279 0,10% 1111 Bearinx-Modell: input side output side DO Loadcase speed torque power Nm kW =kNm/s 1/min 920 2900 279 *~~~* 14 2014/9/23 Screw Machines 2014; 9th International VDI-Conference Ober 🖳 🏟 FAG

Fig. 13: Overview of calculated life times and friction losses

The calculation shows that the original bearing support generates a friction loss of approx. 1.5 kW, which corresponds to approx. 0.56% of the total power.

Bearing variation can be used to reduce the friction to 286 W (corresponding to 0.1%) for an NJ / angular contact ball bearing combination.

Figure 14 below shows a cost comparison that factors in bearing costs and energy consumption costs for the specific alternatives.

20,000 operating hours at  $\in$  0.1 / kWh was used as a calculation base.

Screw Machines 2014; Is low friction efficient?											SCHAEFFLER		
Anal	ytica	l fric	tion a	nalys	sis; oj	otimiza	ition	com	press	or ge	ar		
input side					output side								
axial	price axial bearing	radial	price radial	Total price driving side	radial	price radial	total price bearing	Energie costs (20.000h; 0 1 €/kwh)	savings	total friction	compressor	frictio portic	
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0.101.1	70.07	30219-A	71,20	71,20	30311-A	31,15	102,35	3132	Basis	1566	279	0,56	
QJ214	19,21	NU214	75,57	154,84	NU211 NU211	19,51	1/4,35	701	2309	351	279	0,13	
7214-B 7212-B	36,07	NJ214 NJ212	56,13	92,20	NU212	22,93	115,13	573	2546	286	279	0,13	
Basis:	Bearing qu	antity 200 p	OCS										
		initial type :	= Basis of c	mnarison									
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Fig. 14: Overview of bearing costs, energy costs, and potential savings

A result that needs to be borne in mind is that tapered roller bearings prove to be the most cost-effective bearing solution. Yet the bearing support alternatives with cylindrical roller bearings as radial bearings and four point or angular contact ball bearings as axial bearings exhibit much less friction.

In the TCO calculation, however, the added investment pays for itself many times over, as is clearly indicated in the following bar graph (Fig. 15).



Fig. 15: Comparison of bearing costs and energy costs

The result of the analysis also shows that, when compared to each other, the ball bearing / cylindrical roller bearing alternatives offer only slight advantages for these load cases. The bearing size is particularly decisive here. The compressor manufacturer can select the most favorable alternative depending on the level of reliability desired. In this case, CompAir Drucklufttechnik selected the QJ/NU bearing combination in the end, as it offered advantages for assembly. The test showed a considerably more favorable degree of gearbox efficiency and confirmed the calculations. Since other gearbox points were able to be optimized in addition to the bearing support, the precise improvement due to the bearing change was not able to be quantified in tests.

Another result of the analysis that needs to be borne in mind is that similar kinds of bearing changes produce considerable energy savings when high torque levels need to be transferred at high speeds. At lower torque levels and speeds, the energy gain from reducing friction is not as pronounced. In such cases, the tapered roller bearing support is a reliable and favorable solution.

# Changing the Energy Efficiency Class by Changing to More Cost-Effective Tapered Roller Bearings:

In another analysis, calculations were used to clarify beforehand whether the assignment to a favorable energy efficiency class would still be possible despite changing the rotor bearing support to cost-effective tapered roller bearings. The calculation demonstrated a good probability of continuing to fulfill the requirements of the favorable energy efficiency class. The prototype confirmed the calculation. The compressor was changed over to tapered roller bearings, and the energy efficiency class remained valid.

#### Summary / Conclusion:

In order to assess the overall efficiency of a compressor, aspects besides friction, such as rigidity, temperature behavior, and bearing kinematics, need to be considered.

Calculation software with a mechanical, tribological model enable calculative, comprehensive preliminary investigations during the design phase, in this way presenting decisive optimization options already at this stage and leading compressor manufacturers to the sought-after solution more quickly.

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[1] ISO 15312 Rolling bearings – thermal speed rating – calculation and coefficients