Forschung im Ingenieurwesen (2023) 87:1307–1316
https://doi.org/10.1007/s10010-023-00715-1

ORIGINALARBEITEN/ORIGINALS

Evaluation of friction calculation methods for rolling bearings

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Received: 3 March 2023 / Accepted: 4 September 2023 / Published online: 18 October 2023

Abstract

In gearboxes, rolling bearing power losses often make up a large amount of the total gearbox power losses. Therefore, an exact calculation of rolling bearing power losses is very important for resource and energy efficient gearbox design. The state of the art offers numerous friction calculation methods with different levels of detail to calculate power losses of rolling bearings. Bearing manufacturers like SKF and Schaeffler offer popular bearing-based/global calculation methods for standard rolling bearings. Contact-based/local calculation methods can consider a wider application field by generalization of tribological relations, which enables its application to e.g. hybrid bearings or non-standard bearings. The different methods may yield widely differing results. For its validation, measurement results are required. In this study, a broad comparison of calculation results with substantial measurement results is shown. Based on the validation a classification of the calculation methods is derived, which provides guidance for the design engineer to choose the appropriate method for the respective application. Contact-based/local calculation methods have the potential to predict friction in rolling bearings precisely.

Bewertung von Berechnungsmethoden zur Bestimmung der Wälzlagerreibung

Zusammenfassung

Einen großen Anteil der Getriebeverlustleistung nimmt häufig die Wälzlagerverlustleistung ein. Folglich ist für eine genaue rechnerische Abbildung des Wirkungsgrads und des Wärmehaushalts eines Getriebes die möglichst genaue Berechnung der Wälzlagerverlustleistung von hoher Relevanz. Der Stand der Technik bietet viele unterschiedliche Berechnungsmethoden in verschiedenen Detailstufen zur Berechnung der Wälzlagerverlustleistung an. Mit den Katalogmethoden der Lagerhersteller wie SKF und Schaeffler können die Lagerverlustmomente von Standardlagern unter vereinfachten Lastbedingungen berechnet werden. Kontaktbezogene/lokale Berechnungsmethoden basieren auf den physikalischen Grundbeziehungen von Tribokontakten und können auf ein breiteres Anwendungsfeld wie beispielsweise auch auf Hybridlager oder Sonderlager angewendet werden. Die Berechnungsergebnisse der verschiedenen Methoden weichen zum Teil deutlich voneinander ab. Für eine Validierung der Berechnungsmethoden sind Messergebnisse erforderlich. In dieser Studie wird eine systematische Gegenüberstellung von Berechnungsergebnissen ausgewählter Methoden mit umfassenden Messergebnissen vorgestellt. Anwendungsempfehlungen zu den untersuchten Berechnungsmethoden fassen die gewonnenen Erkenntnisse zusammen und unterstützen den Anwender bei der Auswahl einer geeigneten Berechnungsmethode. Insbesondere kontaktbezogene/lokale Berechnungsmethoden haben das Potenzial die Wälzlagerverlustleistungen präzise vorherzusagen.

Abbreviations

FVA	Research Association for Drive Technology e. V.
FVV	Research Association for Combustion Engines e. V.
LFP	Low Friction Powertrain

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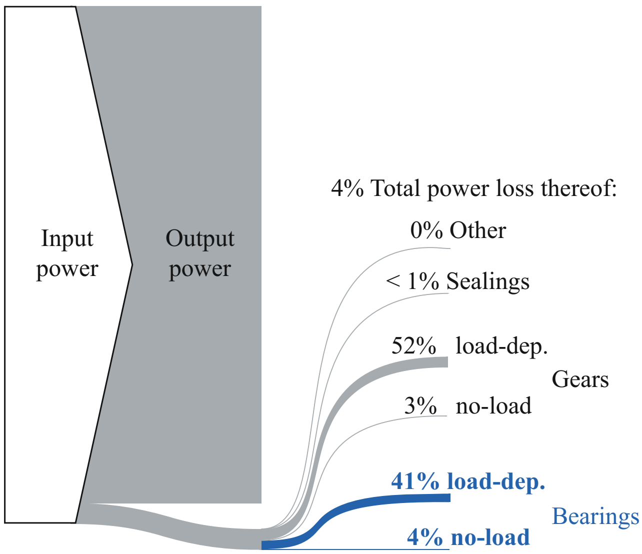

Fig. 1 Exemplary Sankey diagram of power loss in an industrial gearbox from [2]

1 Introduction

Approximately 20% of the world's total energy consumption is used to overcome frictional power losses in tribological contacts [1]. In gearboxes, rolling bearing power losses often make up a large amount of the overall gearbox power losses. Therefore, an exact calculation of rolling bearing power losses is very important for resource and energy efficient gearbox design. Figure 1 shows an example of the power loss portions of an industrial gearbox from [2] according to ISO/TR 14179-2 [3].

The state of the art offers numerous friction calculation methods with different levels of detail to calculate rolling bearing power losses. However, experience from research and industry shows that the agreement with measurement results of the individual calculation methods varies greatly depending on the application [4]. The user lacks a clear overview under which boundary conditions a particular calculation method reliably calculates the bearing friction and hence power loss.

2 Friction calculation methods

Available bearing friction calculation methods can be divided into bearing-based/global methods like Schaeffler [5] or SKF [6] and contact-based/local methods like Schleich [7] or "Low Friction Powertrain" (LFP) [8]. Palmgren [9] developed a bearing-based/global method for the calculation of the bearing frictional torque. Thereby, the bearing frictional torque is divided into a load-dependent portion M_1 and a no-load portion M_0:

$$M = M_1 + M_0 \tag{1}$$

The load-dependent frictional torque M_1 is calculated on the basis of the loaded rolling contacts in the rolling bearing. The no-load frictional torque M_0 depends mainly on the speed and lubrication and describes the hydrodynamic losses due to internal friction in the lubricant in the rolling bearing. This basic method is in adapted form used for calculating the thermal reference speed in ISO 15312-04 [10] and for calculating the loss torque in the current calculation method of Schaeffler [5]:

$$M_{\mathrm{Schaeffler}} = \underbrace{f_1 \cdot P_1 \cdot d_\mathrm{m}}_{M_1} + \underbrace{f_0 \cdot 10^{-7} \cdot (\nu \cdot n)^{\frac{2}{3}} \cdot d_\mathrm{m}{}^3}_{M_0} \tag{2}$$

Schaeffler [11] describes their empirical method [5] as a quick way to "arrive at good approximate values for the frictional torque". The bearing manufacturers NSK and Timken also offer comparable empirical calculation methods based on Palmgren [9, 12, 13]. Also, SKF had specified a method for calculating bearing loss torques based on Palmgren [9, 14]. This was later fundamentally revised [15], so that the bearing frictional torque is divided cause-specifically into four essential parts: rolling friction M_{rr}, sliding friction M_{sl}, seal friction M_{seal} and drag friction from churning and splashing M_{drag}. In the current version, the equation according to [6] is exemplary for ball bearings:

$$\begin{aligned} M_{\mathrm{SKF}} = {} & \underbrace{\Phi_{\mathrm{ish}} \cdot \Phi_{\mathrm{rs}} \cdot G_{\mathrm{rr}} \cdot (\nu \cdot n)^{0.6}}_{M_{\mathrm{rr}}} \\ & + \underbrace{G_{\mathrm{sl}} \cdot (\Phi_\mathrm{s} \cdot \mu_\mathrm{s} + (1 - \Phi_\mathrm{s}) \cdot \mu_{\mathrm{EHL}})}_{M_{\mathrm{sl}}} \\ & + \underbrace{K_{\mathrm{S1}} \cdot d_\mathrm{s}{}^{\beta} + K_{\mathrm{S2}}}_{M_{\mathrm{seal}}} \\ & + \underbrace{\left\{ \begin{matrix} 0.4 \cdot V_\mathrm{M} \cdot K_{\mathrm{ball}} \cdot d_\mathrm{m}{}^5 \cdot n^2 \\ +1.093 \cdot 10^{-7} \cdot n^2 \cdot d_\mathrm{m}{}^3 \cdot \left(\frac{n \cdot d_\mathrm{m}{}^2 \cdot f_\mathrm{t}}{\nu}\right)^{-1.379} \cdot R_\mathrm{S} \end{matrix} \right\}}_{M_{\mathrm{drag}}} \end{aligned} \tag{3}$$

In addition to the catalogue methods, today's developments allow the application of contact-based/local calculation methods based on physical relationships of tribocontacts. Based on the work of Baly [16] and Meyer [17], such a method was developed within the research cluster "Low Friction Powertrain" (LFP) in the project FVV 981 [8]. It was made usable for a wide range of users in industry by integration and further development in LAGER2 [18–20].

The load-dependent frictional torque of the rolling bearing is calculated in the LFP method via a summation of various frictional torque portions from the discretized tribological contacts. The basic equation reads:

$$M_{\mathrm{LFP}} = M_{\mathrm{def}} + M_{\mathrm{roll}} + M_{\mathrm{diff}} + M_{\mathrm{rib}} + M_0 \tag{4}$$

To determine the frictional torque fraction of irreversible deformation M_{def}, the LFP method relies on the approaches of Todd and Johnson [21, 22]. By considering the energy balance of the friction system, the method LFP results in the frictional torque portion due to rolling M_{roll} for ball bearings according to Gohar [23] and Steinert [24]:

$$M_{\mathrm{roll}} = \frac{D_{\mathrm{WK}}}{2} \sum_{\mathrm{i}=1}^{Z} \left[\left| \frac{\omega_{\mathrm{WK}}}{\omega_{\mathrm{IR}}} \right| \left(F_{\mathrm{roll,IR},i} + F_{\mathrm{roll,OR},i} \right) \right] \tag{5}$$

Hereby, the individual frictional torques due to the hydrodynamic rolling forces per rolling element on the inner and outer ring $F_{\mathrm{roll,IR},i} + F_{\mathrm{roll,OR},i}$ are added up. In the case of ball bearings, a significant proportion for micro-sliding friction due to differential slip M_{diff} has to be considered. This is composed of a frictional torque component from the so-called Heathcote slip [25] and the frictional torque component from drilling slip [15, 16] for bearings with non-zero contact angles. The LFP method considers non-Newtonian lubricant behaviour including a limiting shear stress and is essentially based on the work of Zhou and Hoeprich [26]. Equations are also available for conditions with line contact. Additionally, frictional torque from rib contacts M_{rib} in tapered roller bearings are considered. To calculate the no-load portion M_0 of the bearing frictional torque, LFP relies on the methods of Schaeffler [5], SKF [6] or Koryciak [27].

Schleich [6] also developed a contact-based/local method for the calculation of load-dependent bearing frictional torque. The method is also implemented in LAGER2 and, similar to the LFP method, builds on the approach of Steinert [24] or Zhou and Hoeprich [28]. Schleich applies the non-Newtonian lubricant model according to Johnson and Tevaarwerk [29–35]. To calculate the total frictional torque of the rolling bearing, the individual rolling element frictional torques $M_{r,\mathrm{WK},i}$ are summed up, considering the speed ratios between the rolling elements and bearing rings. Additionally, the no-load frictional torque M_0 is added:

$$M_{\mathrm{Schleich}} = \left| \frac{\omega_{\mathrm{WK}}}{\omega_{\mathrm{IR}} - \omega_{\mathrm{OR}}} \right| \cdot \sum_{\mathrm{i}=1}^{Z} M_{\mathrm{r,WK,i}} + M_0 \tag{6}$$

with:

$$M_{\mathrm{r,WK,i}} = \Lambda \cdot M_{\mathrm{solid}} + (1-\Lambda) \cdot M_{\mathrm{fluid}} + M_{\mathrm{def}} \tag{7}$$

Since in mixed lubrication the external load is carried partly via solid contacts and partly via a lubricant film, the load sharing concept based on the solid contact ratio Λ is used. In the Schleich method, as in the SKF method in Eq. 3, the sliding friction force is composed of a solid friction force $F_{\mathrm{r,s}}$ and fluid friction force $F_{\mathrm{r,f}}$. For a surface element A of the discretized single contact, the total frictional force is written as:

$$d\,F_{\mathrm{r}} = \Lambda \cdot \underbrace{p_{\mathrm{H}} \cdot dA \cdot \mu_{\mathrm{s}}}_{d\,F_{\mathrm{r,s}}} + (1-\Lambda) \cdot \underbrace{\tau \cdot dA}_{d\,F_{\mathrm{r,f}}} \tag{8}$$

The fluid friction force $F_{\mathrm{r,f}}$ is calculated from the shear stress τ based on the underlying rheology model [29, 30, 35] based on the Eyring molecular theory [36]. Structural viscous and viscoelastic effects of the lubricant are also considered based on the Maxwell model. The solid contact ratio Λ is a function of the relative lubricant film thickness λ_{rel} and the variables B and C of the rolling partners, which depend on the material and surfaces, according to Zhou [26]:

$$\Lambda = e^{-B \cdot \lambda_{\mathrm{rel}}{}^{C}} \text{ with } \lambda_{\mathrm{rel}} = \frac{h_0}{\sigma} \tag{9}$$

The relative lubricant film thickness results from the ratio of lubricant film thickness and sum roughness of the rolling partners. Thermal effects on the lubricant film thickness are considered according to Zhou and Cheng [28]. With the calculated solid friction force $F_{\mathrm{r,s}}$ and fluid friction force $F_{\mathrm{r,f}}$ and the normal force distribution considering the material damping [21, 22], the frictional torque at each rolling element $M_{r,\mathrm{WK},i}$ can be determined via torque equilibria. To calculate the no-load frictional torque, Schleich refers e.g. to Schaeffler [5] or Koryciak [27].

In addition to open accessible methods from research and literature, there are methods from industry with restricted access to the underlying equations. Examples are Bearinx [37–39] (available as a simplified online version known as "Easy Friction" [40]) and CABA3D [41] from Schaeffler as well as SimPro [42], Bearing Select [43] and BEAST [44, 45] from SKF. Bearinx relies on a contact-based/local method for application modelling and bearing performance analysis. The programs CABA3D and BEAST additionally allow the simulation of dynamic loads.

3 Methodology

For comparison and evaluation with measurement data in this study, four freely accessible methods for the calculation of the bearing frictional force are chosen. These

Table 1 Selected methods for calculation of bearing frictional torques

	Load-dependent	No-load
Schaeffler method [5]	Schaeffler	Schaeffler
SKF method [6]	SKF	SKF
Schleich method [7]	Schleich	Schaeffler
LFP method [8]	LFP	Schaeffler, SKF, Koryciak

Table 2 Bearing friction measurement data from FVA no. 364/IV [46]

Bearing type	Name	Speed n in rpm	LoadC/P	Temp in °C	Lubrication	Kin. viscosity at 40 °C
Deep groove ball bearing	6308 6313 6319	500, 1500, 3000	10 6,5 5	60 90 110	Oil dip lubrication, Oil jet lubrication	32 cSt (FVA2A) 95 cSt (FVA3A) 480 cSt (FVA4A) 64 cSt (PAO10)
Angular contact ball bearing	7308 7313 7319					
Cylindrical roller bearing	NU 308 NU 313 NU 319					
Tapered roller bearing	30308 30313 30319					

are the bearing-based/global catalogue methods Schaeffler and SKF and the contact-based/local methods Schleich and LFP, see Table 1.

It is important to note, that the Schaeffler and SKF methods can calculate both load-dependent and no-load frictional torque within their equations, whereas the Schleich and LFP methods only focus on the load-dependent frictional torque. Hence, for Schleich and LFP the no-load frictional torque has to be calculated e.g. by Schaeffler, SKF or Koryciak. The calculated total rolling bearing frictional torque is obtained by adding the load-dependent and no-load frictional torque.

The FVA no. 364/IV project [46] documents a large number of measurement results on frictional torque and temperatures based on different bearing types and oils as well as load and lubrication conditions (see Table 2). Due to the detailed tabular documentation of the approximately 1800 data sets, these measurement data provide a solid basis to extensively validate and compare calculation methods.

The bearings used in FVA no. 364/IV [46] were subject to a run-in program prior to the test series and thus had conditioned and comparable running surfaces for all operating conditions. For detailed oil and bearing parameters, the reader is referred to the final report of FVA no. 364/IV [46].

The following results focus on deep groove ball bearings and cylindrical roller bearings dip-lubricated with mineral oil FVA3A and with synthetic oil PAO10. Calculation results are compared with measurement results for oil dip lubrication. Thereby, the considered immersion depth in the oil corresponds to the center of the lowest rolling element.

For more detailed results, the reader is referred to the final report of FVA 364/VII [47], which refers to all bearing types and oils in Table 2.

4 Evaluation of friction calculation methods

Figure 2 shows exemplary a comparison of calculation and measurement results for a deep groove ball bearing 6313 dip-lubricated with mineral oil FVA3A (ISO VG 100). The measurement results are highlighted with bold black lines in a limited area. The calculation results with standard parameters of the considered methods are shown in grey. Calculation results with adjusted calculation parameters are shown in the respective colour assigned to the considered calculation method.

The results show that the Schaeffler method overestimates the frictional torque of the investigated deep groove ball bearing. Furthermore, it overestimates the influence from load, but the influence from speed aligns with the trend of the measurement results.

The SKF method shows generally a high agreement with the available measurement results of the deep groove ball bearing. As suggested by Jurkschat for run-in bearings [46], the solid coefficient of friction of the SKF method μ_s is reduced from 0.12 to 0.05. Using this value, the calculation results of the SKF method at low speeds show much better agreement with the measurement results than with μ_s = 0.12.

Using μ_s = 0.12 in the Schleich method the frictional torque is also overestimated, but with μ_s = 0.05, a very

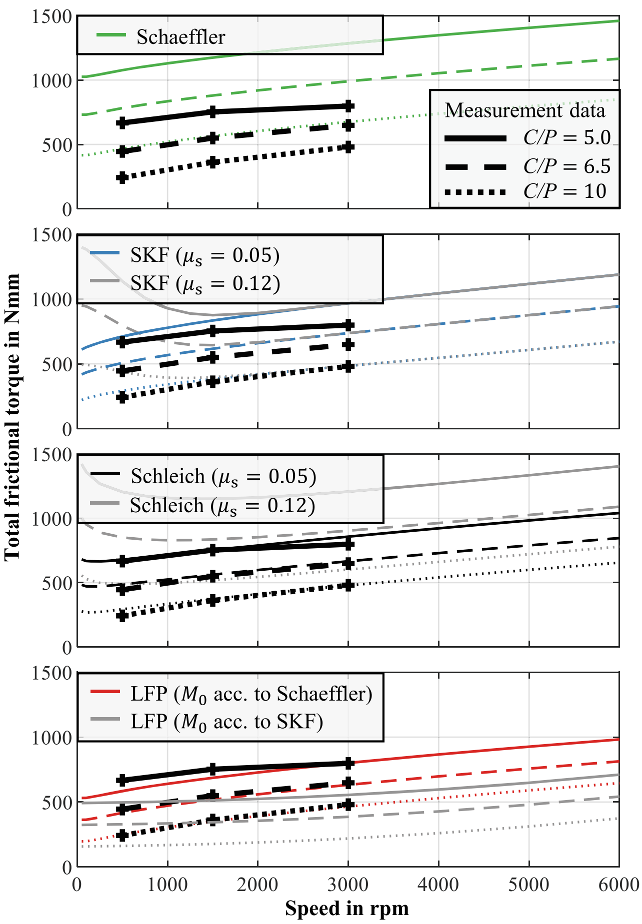

Fig. 2 Comparison of calculated and measured bearing frictional torque for a deep groove ball bearing 6313 dip-lubricated with FVA3A at 90 °C

high agreement with the available measurement results is reached. Also, the influences from speed and load are precisely depicted. The relevant influence of the solid coefficient of friction up to the speed of 6000 rpm suggests a mixed lubrication regime even for higher speeds. This effect can be attributed to the strongly pronounced thermal influence on the lubricant film thickness in the Schleich method. Hence, an increase in speed leads to a relatively strong reduction in lubricant film thickness. This stays in contrast to the results of the SKF method, which indicates full film lubrication regime at above 2000 rpm.

The LFP method with the SKF method used for calculating the no-load frictional torques strongly underestimates the frictional torque and the trend from speed poorly agrees with the measurement results. Using the Schaeffler method to calculate the no-load frictional torque, the LFP method achieves very good agreement with the available measurement results.

Based on these exemplarily results, comparisons between calculation and measurement are shown for a wider spread of operating points. Figure 3 left shows a comparison of the calculated frictional torque, based on the standard parameters of the considered methods, with all available measurement results for deep groove ball bearings dip-lubricated with FVA3A. The size of the markings reflects the respective bearing size, i.e. 6308, 6313 or 6319. The transparency indicates the temperature of the respective operating point. Thereby, 100% transparency refers to low temperature (60 °C) and 0% transparency to high temperature (110 °C).

Figure 3 left confirms the trends of the methods shown in Fig. 2 are also valid for other bearings sizes and oil temperatures. Furthermore, Fig. 3 confirms that the potential for improvement of calculation accuracy by lowering

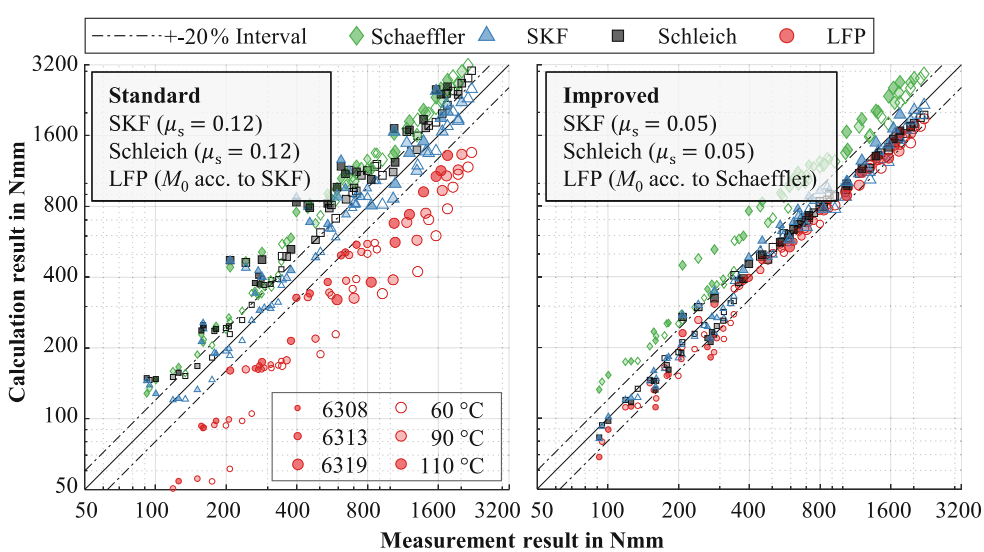

Fig. 3 Comparison of calculated and measured bearing frictional torque for deep groove ball bearings dip-lubricated with the mineral oil FVA3A: Calculation results with standard parameters (*left*) and improved parameters (*right*)

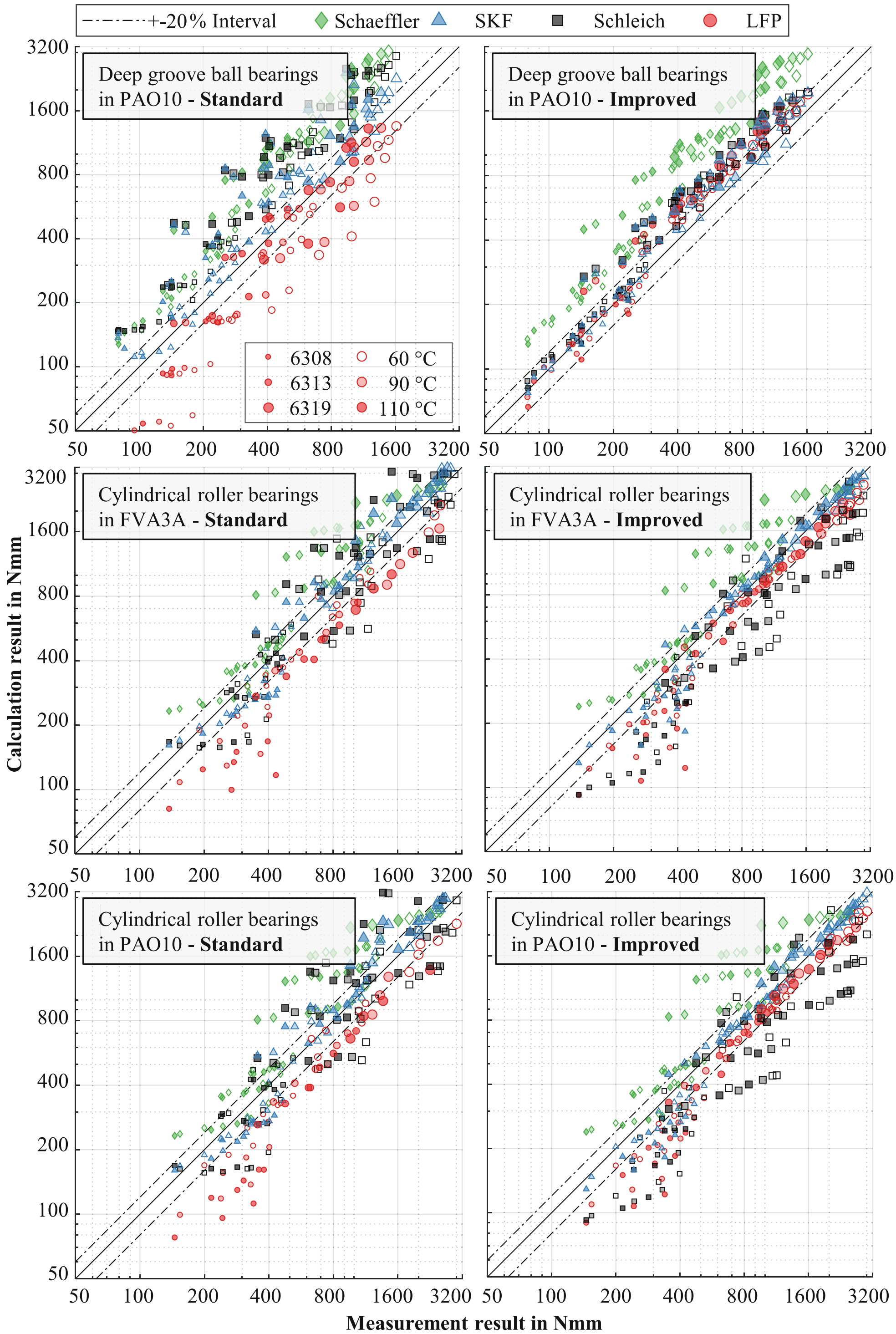

Fig. 4 Comparison of calculated and measured bearing frictional torque for deep groove ball bearings dip-lubricated with the synthetic oil PAO10 (*top*) and for cylindrical roller bearings dip-lubricated with mineral oil FVA3A (*middle*) and synthetic oil PAO10 (*bottom*)

the solid coefficient of friction and by using the Schaeffler method to calculate no-load losses in the LFP method. The average deviation from measurement results is reduced significantly, so that many calculation results are within the 20% interval.

Figure 4 top shows that the observed trends and suggestions for improvements as described above are also determined for deep groove ball bearings dip-lubricated with the synthetic oil PAO10.

Figure 4 middle and bottom shows results for cylindrical roller bearings with mineral oil FVA3A and with synthetic oil PAO10. They show that the Schleich method underestimates friction for the investigated cylindrical bearings, neglecting friction in the roller-rib contacts and friction from

Table 3 Recommended calculation methods depending on bearing type and base oil

	Deep groove ball bearing	Angular contact ball bearing	Cylindrical roller bearing	Tapered roller bearing
Mineral oil	SKF, Schleich, LFP	SKF, Schleich, LFP	SKF, LFP	LFP
Synthetic oil	LFP	Schaeffler	SKF, LFP	LFP

compression of the lubricant in the contact inlet zone. The Schaeffler method, the SKF method and the LFP method lead to calculation results in good agreement with measurement results for cylindrical roller bearings regarding both oils. The SKF method and the LFP method show the lowest deviation to measurement results. As seen for deep groove ball bearings, the suggested improvements also lead to a higher accuracy of the calculation results for cylindrical roller bearings.

Furthermore, it is found, that the calculation temperature has a strong influence on the calculation result, since the bearing frictional torque is significantly dependent on the viscosity of the lubricant. At the operating points investigated, the load-dependent losses usually dominate over the no-load losses. When specifying the mean bearing bulk temperature instead of the oil sump temperature, the accuracy of the calculation methods was improved. Thus, in particular, the contact-based/local calculation methods Schleich and LFP achieve a very high accuracy for certain cases.

Note that the presented results are an extract from the final report of FVA no. 364/VII [47]. By comparing calculation and measurement results for further bearing types and oils of Table 2 more trends regarding bearing type, bearing size, oil temperature, oil viscosity or oil type are revealed.

5 Conclusion

In this paper selected results from a broad calculation study of bearing friction calculation methods for roughly 1300 measured operating points as part of the project FVA no. 364/VII [47] were shown. It was found, that particularly contact-based/local calculation methods have the potential to predict friction in rolling bearings precisely. However, the accuracy of the investigated methods differs strongly in certain cases. Depending on the bearing type and oil type, individual strengths and potentials for improvements were identified and attributed to the different underlying approaches and equations.

Based on the presented results and further results in the final report of FVA no. 364/VII [47], the following conclusions are derived:

- The calculation results of the SKF and Schleich method depend strongly on the solid coefficient of friction. A reduction of the solid coefficient of friction to 0.05 as reported for run-in bearings [46] leads to smaller deviations from measurement results compared to 0.12, as suggested in [6].
- When using the Schaeffler method to consider no-load frictional torque, the LFP method tends to deliver smaller deviations from the measurement results compared to the SKF or Koryciak method.
- The bearing calculation temperature should be chosen as accurate as possible, e.g. using average bearing bulk temperature instead of oil sump temperature. This leads to smaller deviations from measurement results. Considering more than one component temperatures in the calculation (e.g. oil dip and bearing temperature) can lead to more sophisticated results.
- The Schleich method underestimates friction for cylindrical and tapered roller bearings, neglecting friction in the roller-rib contacts and friction from compression of the lubricant in the contact inlet zone. The strongly pronounced thermal influence on the lubricant film thickness in the Schleich method should be checked.

Based on the comparison of the calculation results with measurements for the considered operating conditions, oils and bearing sizes, Table 3 assists the selection of the most suitable calculation method in order to achieve the best calculation accuracy.

6 Nomenclature

The nomenclature is shown in Table 4.

Table 4 Nomenclature

Symbol	Unit	Meaning
A	mm^2	Area
B	–	Variable depending on the material and surfaces acc. to [26]
C	–	Variable depending on the material and surfaces acc. to [26]
d_m	mm	Bearing mean diameter

Table 4 (Continued)

Symbol	Unit	Meaning
d_s	mm	Seal counterface diameter acc. to the SKF method [6]
D_{WK}	mm	Rolling element diameter
f_0	–	Bearing factor for frictional torque as a function of speed acc. to the Schaeffler method [5]
f_1	–	Bearing factor for frictional torque as a function of load acc. to the Schaeffler method [5]
F_r	N	Frictional force of the rolling element
$F_{r,f}$	N	Fluid frictional force of the rolling element
$F_{r,s}$	N	Solid frictional force of the rolling element
$F_{roll,IR/OR}$	N	Hydrodynamic rolling forces per rolling element on the inner and outer ring
f_t	–	Constant acc. to the SKF method [6]
$G_{rr/sl}$	–	Variable depending on the bearing type, the bearing mean diameter, the radial load, the axial load acc. to the SKF method [6]
h_0	µm	Lubricant film thickness
K_{ball}	–	Constant depending on rolling element type acc. to the SKF method [6]
$K_{S1/S2}$	–	Constant depending on the seal type, the bearing type and size acc. to the SKF method [6]
M	Nmm	Bearing frictional torque
M_0	Nmm	No-load bearing frictional torque
M_1	Nmm	Load-dependent bearing frictional torque
M_{def}	Nmm	Frictional torque from irreversible deformation
M_{diff}	Nmm	Sliding frictional torque acc. to the LFP method [8]
M_{drag}	Nmm	Frictional torque from drag losses, churning, splashing, etc. acc. to the SKF method [6]
M_{fluid}	Nmm	Fluid frictional torque acc. to the Schleich method [7]
$M_{Schaeffler}$	Nmm	Bearing frictional torque acc. to the Schaeffler method [5]
M_{LFP}	Nmm	Bearing frictional torque acc. to the LFP method [8]
M_{rib}	Nmm	Frictional torque from rib contacts acc. to the LFP method [8]
M_{roll}	Nmm	Rolling frictional torque
M_{rr}	Nmm	Rolling frictional torque acc. to the SKF method [6]
$M_{r,WK}$	Nmm	Rolling element frictional torque
$M_{Schleich}$	Nmm	Bearing frictional torque acc. to the Schleich method [7]
M_{seal}	Nmm	Frictional torque from seals acc. to the SKF method [6]
M_{SKF}	Nmm	Bearing frictional torque acc. to the SKF method [6]
M_{sl}	Nmm	Sliding frictional torque acc. to the SKF method [6]
M_{solid}	Nmm	Solid frictional torque acc. to the Schleich method [7]
n	–	Operating speed
P_1	N	Decisive load for frictional torque
p_H	N/mm^2	Hertzian pressure
R_s	–	Constant acc. to the SKF method [6]
V_M	–	Drag loss factor acc. to the SKF method [6]
Z	–	Number of rolling elements
β	–	Exponent depending on the seal type and the bearing type acc. to the SKF method [6]
Φ_s	–	Weighting factor for the sliding friction coefficient acc. to the SKF method [6]
Φ_{ish}	–	Inlet shear heating reduction factor acc. to the SKF method [6]
Φ_{rs}	–	Kinematic replenishment/starvation reduction factor acc. to the SKF method [6]
Λ	–	Solid contact ratio
λ_{rel}	µm	Relative lubricant film thickness
μ_{EHL}	–	Sliding friction coefficient in full-film conditions acc. to the SKF method [6]
μ_s	–	Solid coefficient of friction
ν	mm^2/s	Kinematic viscosity of lubricant at operating temperature
σ	µm	Roughness of the rolling partners
$\omega_{IR/OR}$	rad/s	Angular velocity of the inner/outer ring
ω_{WK}	rad/s	Angular velocity of the rolling element around its longitudinal axis

Acknowledgements The presented results are based on the research project FVA no. 364/VII; self-financed by the Research Association for Drive Technology e. V. (FVA). The authors would like to thank for the sponsorship and support received from the FVA and the members of the project committee.

Forschungsvereinigung Antriebstechnik e.V.

Funding Open Access funding enabled and organized by Projekt DEAL.

Conflict of interest M. Zander, M. Otto, T. Lohner and K. Stahl declare that they have no competing interests.

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