The SKF model for calculating the frictional moment

Bearing friction is not constant and depends on certain tribological phenomena that occur in the lubricant film between the rolling elements, raceways and cages.

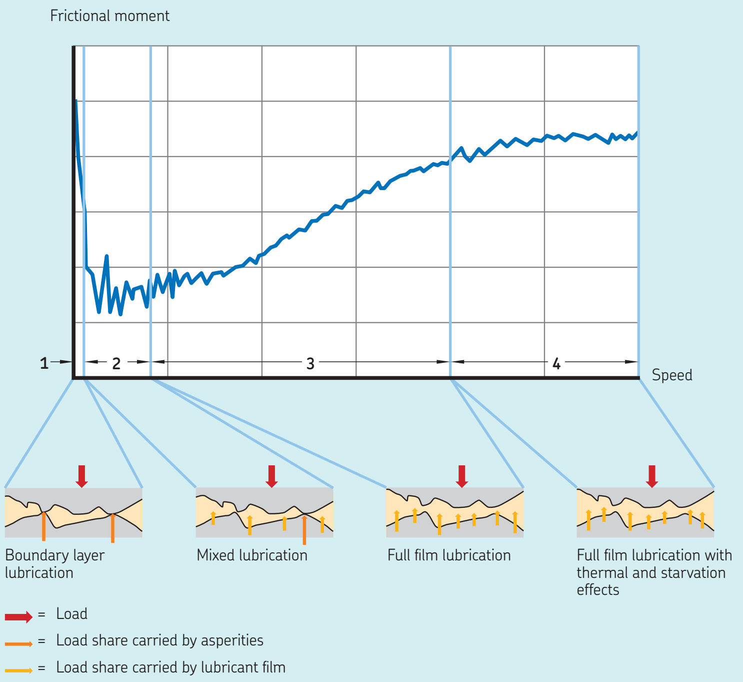
Diagram 1 shows how friction changes, as a function of speed, in a bearing with a given lubricant. Four zones are distinguishable:

- **Zone 1** – Boundary layer lubrication condition, in which only the asperities carry the load, and so friction between the moving surfaces is high.
- **Zone 2** – Mixed lubrication condition, in which a separating oil film carries part of the load, with fewer asperities in contact, and so friction decreases.
- **Zone 3** – Full film lubrication condition, in which the lubricant film carries the load, but with increased viscous losses, and so friction increases.
- **Zone 4** – Full film lubrication with thermal and starvation effects, in which the inlet shear heating and kinematic replenishment reduction factors compensate partially for the viscous losses, and so friction evens off.

To calculate the total frictional moment in a rolling bearing, the following sources and their

Diagram 1

Bearing frictional moment as a function of speed or viscosity



tribological effects must be taken into account:

- the rolling frictional moment and eventual effects of high-speed starvation and inlet shear heating
- the sliding frictional moment and its effect on the quality of the lubrication
- the frictional moment from seal(s)
- the frictional moment from drag losses, churning, splashing etc.

The SKF model for calculating the frictional moment closely follows the real behaviour of the bearing as it considers all contact areas and design changes and improvements made to SKF bearings, including internal and external influences.

The SKF model for calculating the frictional moment uses

$$M = M_{rr} + M_{sl} + M_{seal} + M_{drag}$$

where

M = total frictional moment
M_{rr} = rolling frictional moment
M_{sl} = sliding frictional moment (→ **page 5**)
M_{seal} = frictional moment of seals (→ **page 11**)
M_{drag} = frictional moment of drag losses, churning, splashing etc. (→ **page 12**)

The SKF model is derived from more advanced computational models developed by SKF. It is valid for grease or oil lubricated bearings and is designed to provide approximate reference values under the following application conditions:

- grease lubrication:
  - only steady state conditions (after several hours of operation)
  - lithium soap grease with mineral oil
  - bearing free volume filled approximately 30%
  - ambient temperature 20 °C *(70 °F)* or higher
- oil lubrication:
  - oil bath, oil-air or oil jet
  - viscosity range from 2 to 500 mm²/s
- loads equal to or larger than the recommended minimum load
- constant loads in magnitude and direction
- normal operating clearance
- constant speed, below the speed ratings
- bearing does not exceed the limits of misalignment

For paired bearings, the frictional moment can be calculated separately for each bearing and the results added together. The radial load is divided equally over the two bearings; the axial load is shared according to the bearing arrangement.

NOTE: The formulae provided in this section lead to rather complex calculations. Therefore, SKF strongly recommends calculating the frictional moment using the tools available online at skf.com/bearingcalculator.

Rolling frictional moment

The rolling frictional moment can be calculated using

$$M_{rr} = \Phi_{ish}\, \Phi_{rs}\, G_{rr}\, (\nu\, n)^{0,6}$$

where

M_{rr} = rolling frictional moment [Nmm]
Φ_{ish} = inlet shear heating reduction factor
Φ_{rs} = kinematic replenishment/starvation reduction factor (→ **page 4**)
G_{rr} = variable (→ **table 1**, **page 6**), depending on:
- the bearing type
- the bearing mean diameter d_m [mm] $= 0,5\,(d + D)$
- the radial load F_r [N]
- the axial load F_a [N]

n = rotational speed [r/min]
ν = actual operating viscosity of the oil or the base oil of the grease [mm²/s]

Inlet shear heating reduction factor

A fraction of the overall quantity of oil within a bearing passes through the contact area; only a tiny amount is required to form a hydrodynamic film. Therefore, some of the oil close to the contact area is repelled and produces a reverse flow (→ **fig. 1**). This reverse flow shears the lubricant and generates heat, which lowers the oil viscosity and reduces the film thickness and rolling friction.

For the effect described above, the inlet shear heating reduction factor can be estimated using

$$\Phi_{ish} = \frac{1}{1 + 1{,}84 \times 10^{-9}\,(n\,d_m)^{1{,}28}\,\nu^{0{,}64}}$$

where

Φ_{ish} = inlet shear heating reduction factor (→ **diagram 2**)

n = rotational speed [r/min]

d_m = bearing mean diameter [mm] = 0,5 (d + D)

ν = actual operating viscosity of the oil or the base oil of the grease [mm²/s]

Fig. 1

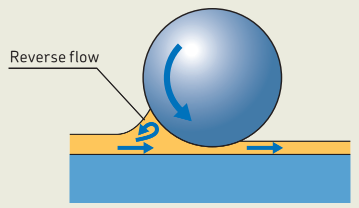
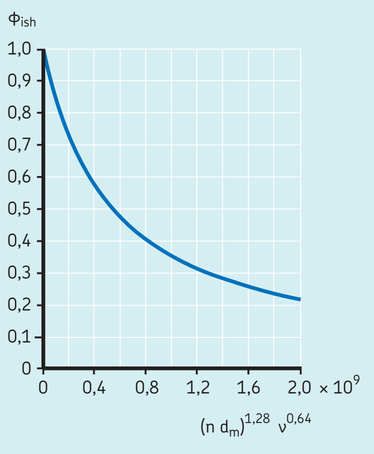


Diagram 2

Inlet shear heating reduction factor Φ_{ish}



Kinematic replenishment/starvation reduction factor

For oil-air, oil jet, low level oil bath lubrication (i.e. oil level H lower than the centre of the lowest rolling element) and grease lubrication methods, continuous over-rolling displaces excess lubricant from the raceways. In applications where viscosity or speeds are high, the lubricant may not have sufficient time to replenish the raceways, causing a “kinematic starvation” effect. Kinematic starvation reduces the thickness of the hydrodynamic film (decreasing κ value) and rolling friction.

For the type of lubrication methods described above, the kinematic replenishment/starvation reduction factor can be estimated using

$$\Phi_{rs} = \frac{1}{e^{\left[K_{rs}\, \nu\, n\, (d + D) \sqrt{\frac{K_z}{2\,(D - d)}}\right]}}$$

where

Φ_{rs} = kinematic replenishment/starvation reduction factor

e = base of natural logarithm ≈ 2,718

K_{rs} = replenishment/starvation constant:
- = 3×10^{-8} low level oil bath and oil jet lubrication
- = 6×10^{-8} grease and oil-air lubrication

K_Z = bearing type related geometric constant (→ **table 4**, **page 14**)

ν = actual operating viscosity of the oil or the base oil of the grease [mm^2/s]

n = rotational speed [r/min]

d = bearing bore diameter [mm]

D = bearing outside diameter [mm]

Sliding frictional moment

The sliding frictional moment can be calculated using

$$M_{sl} = G_{sl}\,\mu_{sl}$$

where

M_{sl} = sliding frictional moment [Nmm]

G_{sl} = variable (→ **table 1, page 6**), depending on:

- the bearing type
- the bearing mean diameter d_m [mm] = 0,5 (d + D)
- the radial load F_r [N]
- the axial load F_a [N]

μ_{sl} = sliding friction coefficient

Effect of lubrication on sliding friction

The sliding friction coefficient for full-film and mixed lubrication conditions can be estimated using

$$\mu_{sl} = \phi_{bl}\,\mu_{bl} + (1 - \phi_{bl})\,\mu_{EHL}$$

where

μ_{sl} = sliding friction coefficient

ϕ_{bl} = weighting factor for the sliding friction coefficient

$$= \frac{1}{e^{2,6 \times 10^{-8}\,(n\,\nu)^{1,4}\,d_m}}$$

(→ **diagram 3**)

e = base of natural logarithm ≈ 2,718

n = rotational speed [r/min]

ν = actual operating viscosity of the oil or the base oil of the grease [mm^2/s]

d_m = bearing mean diameter [mm] = 0,5 (d + D)

μ_{bl} = constant depending on movement:
= 0,12 for n ≠ 0
= 0,15 for n = 0 (starting torque calculation)

μ_{EHL} = sliding friction coefficient in full-film conditions

Values for μ_{EHL} are:

- 0,02 for cylindrical roller bearings
- 0,002 for tapered roller bearings

Other bearings

- 0,05 for lubrication with mineral oils
- 0,04 for lubrication with synthetic oils
- 0,1 for lubrication with transmission fluids

Diagram 3 shows the influence of lubrication conditions on the weighting factor for the sliding friction coefficient:

- For full-film lubrication (corresponding to large values of κ), the value of ϕ_{bl} tends to zero.
- For mixed lubrication, which can occur when lubricant viscosity or the bearing speed is low, the value of ϕ_{bl} tends to 1, as contact between asperities occurs and friction increases.

Diagram 3

Weighting factor ϕ_{bl} for the sliding friction coefficient

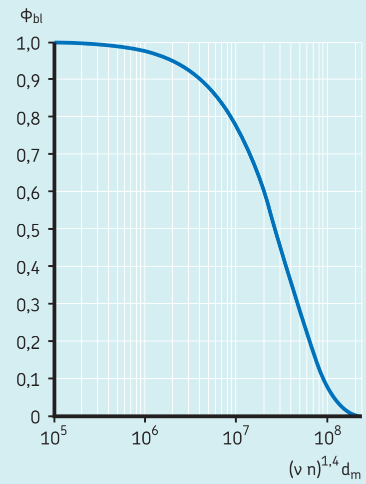


Table 1a

Geometric and load dependent variables for rolling and sliding frictional moments – radial bearings

Bearing type	Rolling frictional variable G_{rr}	Sliding frictional variable G_{sl}
Deep groove ball bearings	when $F_a = 0$ $G_{rr} = R_1\, d_m^{1,96}\, F_r^{0,54}$ when $F_a > 0$ $G_{rr} = R_1\, d_m^{1,96} \left(F_r + \frac{R_2}{\sin \alpha_F} F_a\right)^{0,54}$ $\alpha_F = 24,6\, (F_a/C_0)^{0,24}$ [°]	when $F_a = 0$ $G_{sl} = S_1\, d_m^{-0,26}\, F_r^{5/3}$ when $F_a > 0$ $G_{sl} = S_1\, d_m^{-0,145} \left(F_r^5 + \frac{S_2\, d_m^{1,5}}{\sin \alpha_F} F_a^4\right)^{1/3}$
Angular contact ball bearings[1]	$G_{rr} = R_1\, d_m^{1,97}\, [F_r + F_g + R_2\, F_a]^{0,54}$ $F_g = R_3\, d_m^4\, n^2$	$G_{sl} = S_1\, d_m^{0,26}\, [(F_r + F_g)^{4/3} + S_2\, F_a^{4/3}]$ $F_g = S_3\, d_m^4\, n^2$
Four-point contact ball bearings	$G_{rr} = R_1\, d_m^{1,97}\, [F_r + F_g + R_2\, F_a]^{0,54}$ $F_g = R_3\, d_m^4\, n^2$	$G_{sl} = S_1\, d_m^{0,26}\, [(F_r + F_g)^{4/3} + S_2\, F_a^{4/3}]$ $F_g = S_3\, d_m^4\, n^2$
Self-aligning ball bearings	$G_{rr} = R_1\, d_m^2\, [F_r + F_g + R_2\, F_a]^{0,54}$ $F_g = R_3\, d_m^{3,5}\, n^2$	$G_{sl} = S_1\, d_m^{-0,12}\, [(F_r + F_g)^{4/3} + S_2\, F_a^{4/3}]$ $F_g = S_3\, d_m^{3,5}\, n^2$
Cylindrical roller bearings	$G_{rr} = R_1\, d_m^{2,41}\, F_r^{0,31}$	$G_{sl} = S_1\, d_m^{0,9}\, F_a + S_2\, d_m\, F_r$
Tapered roller bearings[1] For the axial load factor Y for single row bearings → **product tables**	$G_{rr} = R_1\, d_m^{2,38}\, (F_r + R_2\, Y\, F_a)^{0,31}$	$G_{sl} = S_1\, d_m^{0,82}\, (F_r + S_2\, Y\, F_a)$
Spherical roller bearings	$G_{rr.e} = R_1\, d_m^{1,85}\, (F_r + R_2\, F_a)^{0,54}$ $G_{rr.l} = R_3\, d_m^{2,3}\, (F_r + R_4\, F_a)^{0,31}$ when $G_{rr.e} < G_{rr.l}$ $G_{rr} = G_{rr.e}$ otherwise $G_{rr} = G_{rr.l}$	$G_{sl.e} = S_1\, d_m^{0,25}\, (F_r^4 + S_2\, F_a^4)^{1/3}$ $G_{sl.l} = S_3\, d_m^{0,94}\, (F_r^3 + S_4\, F_a^3)^{1/3}$ when $G_{sl.e} < G_{sl.l}$ $G_{sl} = G_{sl.e}$ otherwise $G_{sl} = G_{sl.l}$
CARB toroidal roller bearings	when $F_r < (R_2^{1,85}\, d_m^{0,78}/R_1^{1,85})^{2,35}$ $G_{rr} = R_1\, d_m^{1,97}\, F_r^{0,54}$ otherwise $G_{rr} = R_2\, d_m^{2,37}\, F_r^{0,31}$	when $F_r < (S_2\, d_m^{1,24}/S_1)^{1,5}$ $G_{sl} = S_1\, d_m^{-0,19}\, F_r^{5/3}$ otherwise $G_{sl} = S_2\, d_m^{1,05}\, F_r$

The geometry constants R and S are listed in **table 2**, starting on **page 8**.
Both loads, F_r and F_a are always considered as positive.
[1] The value to be used for F_a is the external axial load.

Table 1b

Geometric and load dependent variables for rolling and sliding frictional moments – thrust bearings

Bearing type	Rolling frictional variable G_{rr}	Sliding frictional variable G_{sl}
Thrust ball bearings	$G_{rr} = R_1\, d_m^{1,83}\, F_a^{0,54}$	$G_{sl} = S_1\, d_m^{0,05}\, F_a^{4/3}$
Cylindrical roller thrust bearings	$G_{rr} = R_1\, d_m^{2,38}\, F_a^{0,31}$	$G_{sl} = S_1\, d_m^{0,62}\, F_a$
Spherical roller thrust bearings	$G_{rr.e} = R_1\, d_m^{1,96}\, (F_r + R_2\, F_a)^{0,54}$ $G_{rr.l} = R_3\, d_m^{2,39}\, (F_r + R_4\, F_a)^{0,31}$ when $G_{rr.e} < G_{rr.l}$ $G_{rr} = G_{rr.e}$ otherwise $G_{rr} = G_{rr.l}$	$G_{sl.e} = S_1\, d_m^{-0,35}\, (F_r^{5/3} + S_2\, F_a^{5/3})$ $G_{sl.l} = S_3\, d_m^{0,89}\, (F_r + F_a)$ when $G_{sl.e} < G_{sl.l}$ $G_{sr} = G_{sl.e}$ otherwise $G_{sr} = G_{sl.l}$ $G_f = S_4\, d_m^{0,76}\, (F_r + S_5\, F_a)$ $G_{sl} = G_{sr} + \dfrac{G_f}{e^{10^{-6}\,(n\,\nu)^{1,4}\, d_m}}$

Table 2

Geometric constants for rolling and sliding frictional moments

Bearing type	Geometric constants for rolling frictional moments R_1	R_2	R_3	sliding frictional moments S_1	S_2	S_3
Deep groove ball bearings	(→ **table 2a**)			(→ **table 2a**)		
Angular contact ball bearings						
– Single row 40°						
72 B(E) series	$4,33 \times 10^{-7}$	2,02	$2,44 \times 10^{-12}$	$1,82 \times 10^{-2}$	0,71	$2,44 \times 10^{-12}$
73 B(E) series	$4,54 \times 10^{-7}$	2,02	$1,84 \times 10^{-12}$	$1,64 \times 10^{-2}$	0,71	$1,84 \times 10^{-12}$
– Single row 25°						
72 AC series	$3,58 \times 10^{-7}$	3,64	$3,55 \times 10^{-12}$	$1,14 \times 10^{-2}$	1,55	$3,55 \times 10^{-12}$
73 AC series	$3,48 \times 10^{-7}$	3,64	$1,66 \times 10^{-12}$	$9,85 \times 10^{-3}$	1,55	$1,66 \times 10^{-12}$
– all other single row	$5,03 \times 10^{-7}$	1,97	$1,90 \times 10^{-12}$	$1,30 \times 10^{-2}$	0,68	$1,91 \times 10^{-12}$
– Double row 30°						
32 A series	$5,18 \times 10^{-7}$	1,63	$4,18 \times 10^{-12}$	$1,08 \times 10^{-2}$	1,47	$4,18 \times 10^{-12}$
33 A series	$5,31 \times 10^{-7}$	1,63	$8,83 \times 10^{-13}$	$5,48 \times 10^{-3}$	1,47	$8,83 \times 10^{-13}$
– all other double row	$6,34 \times 10^{-7}$	1,41	$7,83 \times 10^{-13}$	$7,56 \times 10^{-3}$	1,21	$7,83 \times 10^{-13}$
– four-point contact	$4,78 \times 10^{-7}$	2,42	$1,40 \times 10^{-12}$	$1,20 \times 10^{-2}$	0,9	$1,40 \times 10^{-12}$
Self-aligning ball bearings	(→ **table 2b**)			(→ **table 2b**)		
Cylindrical roller bearings	(→ **table 2c**)			(→ **table 2c**)		
Tapered roller bearings	(→ **table 2d**)			(→ **table 2d**)		
Spherical roller bearings	(→ **table 2e**)			(→ **table 2e**)		
CARB toroidal roller bearings	(→ **table 2f**)			(→ **table 2f**)		
Thrust ball bearings	$1,03 \times 10^{-6}$			$1,6 \times 10^{-2}$		
Cylindrical roller thrust bearings	$2,25 \times 10^{-6}$			0,154		
Spherical roller thrust bearings	(→ **table 2g**)			(→ **table 2g**)		

Table 2a

Geometric constants for rolling and sliding frictional moments of deep groove ball bearings

Bearing series	Geometric constants for rolling frictional moments R_1	R_2	sliding frictional moments S_1	S_2
2, 3	$4,4 \times 10^{-7}$	1,7	$2,00 \times 10^{-3}$	100
42, 43	$5,4 \times 10^{-7}$	0,96	$3,00 \times 10^{-3}$	40
60, 630	$4,1 \times 10^{-7}$	1,7	$3,73 \times 10^{-3}$	14,6
62, 622	$3,9 \times 10^{-7}$	1,7	$3,23 \times 10^{-3}$	36,5
63, 623	$3,7 \times 10^{-7}$	1,7	$2,84 \times 10^{-3}$	92,8
64	$3,6 \times 10^{-7}$	1,7	$2,43 \times 10^{-3}$	198
160, 161	$4,3 \times 10^{-7}$	1,7	$4,63 \times 10^{-3}$	4,25
617, 618, 628, 637, 638	$4,7 \times 10^{-7}$	1,7	$6,50 \times 10^{-3}$	0,78
619, 639	$4,3 \times 10^{-7}$	1,7	$4,75 \times 10^{-3}$	3,6

Table 2b

Geometric constants for rolling and sliding frictional moments of self-aligning ball bearings

Bearing series	Geometric constants for rolling frictional moments R_1	R_2	R_3	sliding frictional moments S_1	S_2	S_3
12	$3,25 \times 10^{-7}$	6,51	$2,43 \times 10^{-12}$	$4,36 \times 10^{-3}$	9,33	$2,43 \times 10^{-12}$
13	$3,11 \times 10^{-7}$	5,76	$3,52 \times 10^{-12}$	$5,76 \times 10^{-3}$	8,03	$3,52 \times 10^{-12}$
22	$3,13 \times 10^{-7}$	5,54	$3,12 \times 10^{-12}$	$5,84 \times 10^{-3}$	6,60	$3,12 \times 10^{-12}$
23	$3,11 \times 10^{-7}$	3,87	$5,41 \times 10^{-12}$	0,01	4,35	$5,41 \times 10^{-12}$
112	$3,25 \times 10^{-7}$	6,16	$2,48 \times 10^{-12}$	$4,33 \times 10^{-3}$	8,44	$2,48 \times 10^{-12}$
130	$2,39 \times 10^{-7}$	5,81	$1,10 \times 10^{-12}$	$7,25 \times 10^{-3}$	7,98	$1,10 \times 10^{-12}$
139	$2,44 \times 10^{-7}$	7,96	$5,63 \times 10^{-13}$	$4,51 \times 10^{-3}$	12,11	$5,63 \times 10^{-13}$

Table 2c

Geometric constants for rolling and sliding frictional moments of cylindrical roller bearings

Bearing series	Geometric constants for rolling frictional moments R_1	sliding frictional moments S_1	S_2
Bearing with cage of the N, NU, NJ or NUP design			
2, 3	$1,09 \times 10^{-6}$	0,16	0,0015
4	$1,00 \times 10^{-6}$	0,16	0,0015
10	$1,12 \times 10^{-6}$	0,17	0,0015
12, 20	$1,23 \times 10^{-6}$	0,16	0,0015
22	$1,40 \times 10^{-6}$	0,16	0,0015
23	$1,48 \times 10^{-6}$	0,16	0,0015
High capacity bearings with cage of the NCF .. ECJB, RN .. ECJB, NJF .. ECJA, RNU .. ECJA or NUH .. ECMH design			
22	$1,54 \times 10^{-6}$	0,16	0,0015
23	$1,63 \times 10^{-6}$	0,16	0,0015
Full complement bearings of the NCF, NJG, NNCL, NNCF, NNC or NNF design			
All series	$2,13 \times 10^{-6}$	0,16	0,0015

Table 2d

Geometric constants for rolling and sliding frictional moments of tapered roller bearings

Bearing series	Geometric constants for rolling frictional moments R_1	R_2	sliding frictional moments S_1	S_2
302	$1,76 \times 10^{-6}$	10,9	0,017	2
303	$1,69 \times 10^{-6}$	10,9	0,017	2
313 (X)	$1,84 \times 10^{-6}$	10,9	0,048	2
320 X	$2,38 \times 10^{-6}$	10,9	0,014	2
322	$2,27 \times 10^{-6}$	10,9	0,018	2
322 B	$2,38 \times 10^{-6}$	10,9	0,026	2
323	$2,38 \times 10^{-6}$	10,9	0,019	2
323 B	$2,79 \times 10^{-6}$	10,9	0,030	2
329	$2,31 \times 10^{-6}$	10,9	0,009	2
330	$2,71 \times 10^{-6}$	11,3	0,010	2
331	$2,71 \times 10^{-6}$	10,9	0,015	2
332	$2,71 \times 10^{-6}$	10,9	0,018	2
LL	$1,72 \times 10^{-6}$	10,9	0,0057	2
L	$2,19 \times 10^{-6}$	10,9	0,0093	2
LM	$2,25 \times 10^{-6}$	10,9	0,011	2
M	$2,48 \times 10^{-6}$	10,9	0,015	2
HM	$2,60 \times 10^{-6}$	10,9	0,020	2
H	$2,66 \times 10^{-6}$	10,9	0,025	2
HH	$2,51 \times 10^{-6}$	10,9	0,027	2
All other	$2,31 \times 10^{-6}$	10,9	0,019	2

Table 2e

Geometric constants for rolling and sliding frictional moments of spherical roller bearings

Bearing series	Geometric constants for rolling frictional moments				sliding frictional moments			
	R_1	R_2	R_3	R_4	S_1	S_2	S_3	S_4
213 E, 222 E	$1,6 \times 10^{-6}$	5,84	$2,81 \times 10^{-6}$	5,8	$3,62 \times 10^{-3}$	508	$8,8 \times 10^{-3}$	117
222	$2,0 \times 10^{-6}$	5,54	$2,92 \times 10^{-6}$	5,5	$5,10 \times 10^{-3}$	414	$9,7 \times 10^{-3}$	100
223	$1,7 \times 10^{-6}$	4,1	$3,13 \times 10^{-6}$	4,05	$6,92 \times 10^{-3}$	124	$1,7 \times 10^{-2}$	41
223 E	$1,6 \times 10^{-6}$	4,1	$3,14 \times 10^{-6}$	4,05	$6,23 \times 10^{-3}$	124	$1,7 \times 10^{-2}$	41
230	$2,4 \times 10^{-6}$	6,44	$3,76 \times 10^{-6}$	6,4	$4,13 \times 10^{-3}$	755	$1,1 \times 10^{-2}$	160
231	$2,4 \times 10^{-6}$	4,7	$4,04 \times 10^{-6}$	4,72	$6,70 \times 10^{-3}$	231	$1,7 \times 10^{-2}$	65
232	$2,3 \times 10^{-6}$	4,1	$4,00 \times 10^{-6}$	4,05	$8,66 \times 10^{-3}$	126	$2,1 \times 10^{-2}$	41
238	$3,1 \times 10^{-6}$	12,1	$3,82 \times 10^{-6}$	12	$1,74 \times 10^{-3}$	9 495	$5,9 \times 10^{-3}$	1 057
239	$2,7 \times 10^{-6}$	8,53	$3,87 \times 10^{-6}$	8,47	$2,77 \times 10^{-3}$	2 330	$8,5 \times 10^{-3}$	371
240	$2,9 \times 10^{-6}$	4,87	$4,78 \times 10^{-6}$	4,84	$6,95 \times 10^{-3}$	240	$2,1 \times 10^{-2}$	68
241	$2,6 \times 10^{-6}$	3,8	$4,79 \times 10^{-6}$	3,7	$1,00 \times 10^{-2}$	86,7	$2,9 \times 10^{-2}$	31
248	$3,8 \times 10^{-6}$	9,4	$5,09 \times 10^{-6}$	9,3	$2,80 \times 10^{-3}$	3 415	$1,2 \times 10^{-2}$	486
249	$3,0 \times 10^{-6}$	6,67	$5,09 \times 10^{-6}$	6,62	$3,90 \times 10^{-3}$	887	$1,7 \times 10^{-2}$	180

Table 2f

Geometric constants for rolling and sliding frictional moments of CARB toroidal roller bearings with a cage

Bearing series	Geometric constants for rolling frictional moments		sliding frictional moments	
	R_1	R_2	S_1	S_2
C 22	$1,17 \times 10^{-6}$	$2,08 \times 10^{-6}$	$1,32 \times 10^{-3}$	$0,8 \times 10^{-2}$
C 23	$1,20 \times 10^{-6}$	$2,28 \times 10^{-6}$	$1,24 \times 10^{-3}$	$0,9 \times 10^{-2}$
C 30	$1,40 \times 10^{-6}$	$2,59 \times 10^{-6}$	$1,58 \times 10^{-3}$	$1,0 \times 10^{-2}$
C 31	$1,37 \times 10^{-6}$	$2,77 \times 10^{-6}$	$1,30 \times 10^{-3}$	$1,1 \times 10^{-2}$
C 32	$1,33 \times 10^{-6}$	$2,63 \times 10^{-6}$	$1,31 \times 10^{-3}$	$1,1 \times 10^{-2}$
C 39	$1,45 \times 10^{-6}$	$2,55 \times 10^{-6}$	$1,84 \times 10^{-3}$	$1,0 \times 10^{-2}$
C 40	$1,53 \times 10^{-6}$	$3,15 \times 10^{-6}$	$1,50 \times 10^{-3}$	$1,3 \times 10^{-2}$
C 41	$1,49 \times 10^{-6}$	$3,11 \times 10^{-6}$	$1,32 \times 10^{-3}$	$1,3 \times 10^{-2}$
C 49	$1,49 \times 10^{-6}$	$3,24 \times 10^{-6}$	$1,39 \times 10^{-3}$	$1,5 \times 10^{-2}$
C 59	$1,77 \times 10^{-6}$	$3,81 \times 10^{-6}$	$1,80 \times 10^{-3}$	$1,8 \times 10^{-2}$
C 60	$1,83 \times 10^{-6}$	$5,22 \times 10^{-6}$	$1,17 \times 10^{-3}$	$2,8 \times 10^{-2}$
C 69	$1,85 \times 10^{-6}$	$4,53 \times 10^{-6}$	$1,61 \times 10^{-3}$	$2,3 \times 10^{-2}$

Table 2g

Geometric constants for rolling and sliding frictional moments of spherical roller thrust bearings

Bearing series	Geometric constants for rolling frictional moments				sliding frictional moments				
	R_1	R_2	R_3	R_4	S_1	S_2	S_3	S_4	S_5
292	$1,32 \times 10^{-6}$	1,57	$1,97 \times 10^{-6}$	3,21	$4,53 \times 10^{-3}$	0,26	0,02	0,1	0,6
292 E	$1,32 \times 10^{-6}$	1,65	$2,09 \times 10^{-6}$	2,92	$5,98 \times 10^{-3}$	0,23	0,03	0,17	0,56
293	$1,39 \times 10^{-6}$	1,66	$1,96 \times 10^{-6}$	3,23	$5,52 \times 10^{-3}$	0,25	0,02	0,1	0,6
293 E	$1,16 \times 10^{-6}$	1,64	$2,00 \times 10^{-6}$	3,04	$4,26 \times 10^{-3}$	0,23	0,025	0,15	0,58
294 E	$1,25 \times 10^{-6}$	1,67	$2,15 \times 10^{-6}$	2,86	$6,42 \times 10^{-3}$	0,21	0,04	0,2	0,54

Frictional moment of seals

Where bearings are fitted with contact seals, the frictional losses from the seals may exceed those generated by the bearing. The frictional moment of seals for bearings that are sealed on both sides can be estimated using

$$M_{seal} = K_{S1}\, d_s^{\beta} + K_{S2}$$

where

M_{seal} = frictional moment of seals [Nmm]

K_{S1} = constant (→ **table 3**), depending on:
- the seal type
- the bearing type and size

d_s = seal counterface diameter [mm] (→ **table 3**)

β = exponent (→ **table 3**), depending on:
- the seal type
- the bearing type

K_{S2} = constant (→ **table 3**), depending on:
- the seal type
- the bearing type and size

In cases where there is only one seal, the friction generated is 0,5 M_{seal}.

For deep groove ball bearings with RSL seals and D > 25 mm, use the calculated value of M_{seal}, irrespective whether there is one or two seals.

Table 3

Seal frictional moment: Exponent and constants

Seal type Bearing type	**Bearing outside diameter [mm]** D over	incl.	**Exponent and constants** β	K_{S1}	K_{S2}	**Seal counterface diameter** d_s[1]
RSL seals						
Deep groove ball bearings	–	25	0	0	0	d_2
	25	52	2,25	0,0018	0	d_2
RSH seals						
Deep groove ball bearings	–	52	2,25	0,028	2	d_2
RS1 seals						
Deep groove ball bearings	–	62	2,25	0,023	2	d_1, d_2
	62	80	2,25	0,018	20	d_1, d_2
	80	100	2,25	0,018	15	d_1, d_2
	100		2,25	0,018	0	d_1, d_2
Angular contact ball bearings	30	120	2	0,014	10	d_1
Self-aligning ball bearings	30	125	2	0,014	10	d_2
LS seals						
Cylindrical roller bearings	42	360	2	0,032	50	E
CS, CS2 and CS5 seals						
Spherical roller bearings	62	300	2	0,057	50	d_2
CARB toroidal roller bearings	42	340	2	0,057	50	d_2

[1] Designation of the dimension listed in the product tables

Drag losses

Bearings lubricated by the oil bath method are partially submerged or, in special situations, completely submerged. The drag losses that occur when the bearing is rotating in an oil bath contribute to the total frictional moment and should not be ignored. Drag losses are not only influenced by bearing speed, oil viscosity and oil level, but also by the size and geometry of the oil reservoir. External oil agitation, which can originate from mechanical elements, such as gears or cams, in close proximity to the bearing should also be taken into consideration.

Drag losses in oil bath lubrication

The SKF model for calculating drag losses in oil bath lubrication considers the resistance of the rolling elements moving through the oil and includes the effects of the oil viscosity. It provides results with sufficient accuracy under the following conditions:

- The oil reservoir is large. Effects from reservoir size and geometry or external oil agitation are negligible.
- The shaft is horizontal.
- The inner ring rotates at a constant speed. The speed does not exceed the permissible speed.
- The oil viscosity is within the limits:
  - $\leq 500\ \text{mm}^2/\text{s}$ when the bearing is submerged up to, and including, half of its outside diameter (oil level $H \leq D/2$)
  - $\leq 250\ \text{mm}^2/\text{s}$ when the bearing is submerged more than half of its outside diameter (oil level $H > D/2$)

The oil level H is measured from the lowest contact point between the outer ring raceway and the rolling element (→ **fig. 2**, **page 14**). The postion of the lowest contact point can be estimated with sufficient accuracy using:

- for tapered roller bearings: outside diameter D [mm]
- for all other radial rolling bearings: outer ring mean diameter [mm] $= 0,5\,(D + D_1)$

The frictional moment of drag losses for ball bearings can be estimated using

$$M_{drag} = 0{,}4\, V_M\, K_{ball}\, d_m^{\,5}\, n^2 + 1{,}093 \times 10^{-7}\, n^2\, d_m^{\,3} \left(\frac{n\, d_m^{\,2}\, f_t}{\nu}\right)^{-1{,}379} R_s$$

The frictional moment of drag losses for roller bearings can be estimated using

$$M_{drag} = 4\, V_M\, K_{roll}\, C_w\, B\, d_m^{\,4}\, n^2 + 1{,}093 \times 10^{-7}\, n^2\, d_m^{\,3} \left(\frac{n\, d_m^{\,2}\, f_t}{\nu}\right)^{-1{,}379} R_s$$

The rolling element related constants are:

$$K_{ball} = \frac{i_{rw}\, K_z\, (d + D)}{D - d}\, 10^{-12}$$

$$K_{roll} = \frac{K_L\, K_Z\, (d + D)}{D - d}\, 10^{-12}$$

The variables and functions used in the equations for the frictional moment of drag losses are:

$$C_w = 2,789 \times 10^{-10}\, l_D^3 - 2,786 \times 10^{-4}\, l_D^2 + 0,0195\, l_D + 0,6439$$

$$l_D = 5\,\frac{K_L\, B}{d_m}$$

$$f_t = \begin{cases} \sin(0,5\, t), & \text{when } 0 \le t \le \pi \\ 1, & \text{when } \pi < t < 2\,\pi \end{cases}$$

$$R_s = 0,36\, d_m^2\, (t - \sin t)\, f_A$$

$$t = 2\cos^{-1}\left(\frac{0,6\, d_m - H}{0,6\, d_m}\right) \qquad \text{When } H \ge 1,2\, d_m\text{, use } H = 1,2\, d_m$$

$$f_A = 0,05\;\frac{K_z\,(D + d)}{D - d}$$

where

M_{drag} = frictional moment of drag losses [Nmm]

V_M = drag loss factor (→ **diagram 4**, **page 14**)

B = bearing width [mm]

- for tapered roller bearings → width T
- for thrust bearings → height H

d_m = bearing mean diameter [mm] = 0,5 (d + D)

d = bearing bore diameter [mm]

D = bearing outside diameter [mm]

H = oil level (→ **fig. 2**, **page 14**) [mm]

i_{rw} = number of ball rows

K_Z = bearing type related geometric constant (→ **table 4**, **page 14**)

K_L = roller bearing type related geometric constant (→ **table 4**, **page 14**)

n = rotational speed [r/min]

ν = actual operating viscosity of the lubricant [mm²/s]

Drag losses for vertical shafts

The model for fully submerged bearings can be used to calculate an approximate value of the drag losses for vertical shaft arrangements. The value obtained for M_{drag} should be multiplied by a factor equal to the width (height) that is submerged relative to the total bearing width (height).

Drag losses for oil jet lubrication

To calculate drag losses for the oil jet lubrication method, use the oil bath model, with the oil level H at half the diameter of the lowest rolling element. The value obtained for M_{drag} should be multiplied by a factor of two. Certainly, this approximation can vary depending on the rate and direction of oil flow. However, if the oil level H is known when oil is flowing and the bearing is at a stand-still, this value can be used directly in the drag loss calculation to obtain a more accurate estimate.

Table 4

Geometric constants K_Z and K_L

Bearing type	Geometric constants K_Z	K_L
Deep groove ball bearings		
– single and double row	3,1	–
Angular contact ball bearings		
– single row	4,4	–
– double row	3,1	–
– four-point contact	3,1	–
Self-aligning ball bearings	4,8	–
Cylindrical roller bearings		
– with a cage	5,1	0,65
– full complement	6,2	0,7
Tapered roller bearings	6	0,7
Spherical roller bearings	5,5	0,8
CARB toroidal roller bearings		
– with a cage	5,3	0,8
– full complement	6	0,75
Thrust ball bearings	3,8	–
Cylindrical roller thrust bearings	4,4	0,43
Spherical roller thrust bearings	5,6	0,58[1]

[1] Only for single mounted bearings

Fig. 2

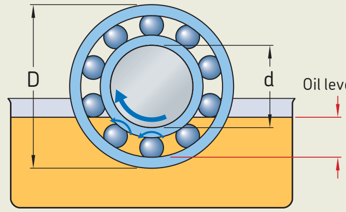
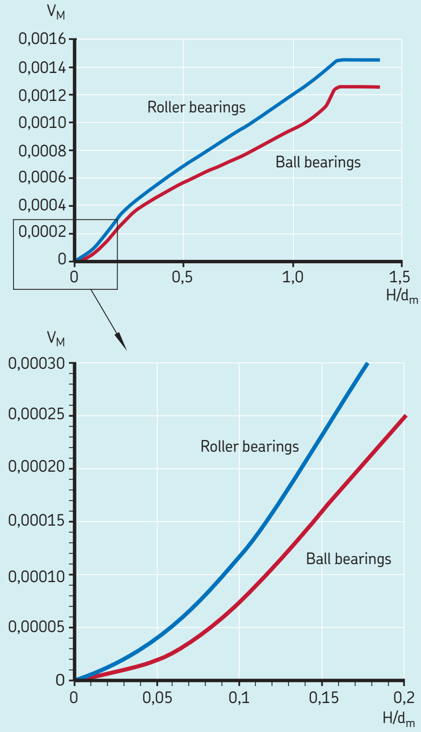


Diagram 4

Drag loss factor V_M



Additional effects on the frictional moment

Effects of clearance and misalignment on friction

Changes in clearance or misalignment in bearings influence the frictional moment. The model considers normal internal operating clearance and an aligned bearing. However, high bearing operating temperatures or speeds might reduce internal bearing clearance, which can increase friction. Misalignment generally increases friction. However, for self-aligning ball bearings, spherical roller bearings, CARB toroidal roller bearings and spherical roller thrust bearings, the corresponding increase of friction is negligible.

Effects of grease fill on friction

When a bearing has just been lubricated or relubricated with the recommended amount of grease, the frictional values realized in the bearing can be much higher than those originally calculated. The effect can be seen as an increase in operating temperature. The time it takes for friction to decrease depends on the speed of the application and the time it takes for the grease to distribute itself within the free space in the bearing.

This effect can be estimated by multiplying the rolling frictional moment by a factor of 2 to 4, where 2 applies for light series bearings (narrow width series) and 4 for heavy series bearings.

However, after the running-in period, the frictional moment in the bearing is similar to, or even lower than, that for oil lubricated bearings. Bearings filled with an excessive amount of grease may show higher frictional values.

Additional information for specific bearing types and performance classes

Hybrid bearings

The higher values for the modulus of elasticity of rolling elements made of silicon nitride decreases the contact area in the raceways to significantly reduce rolling and sliding friction. Additionally, the lower density of ceramic rolling elements, when compared with steel, reduces the centrifugal forces, which also may reduce friction at high speeds.

Standard hybrid ball bearings

Using the above equations, the frictional moment for hybrid angular contact ball bearings can be calculated by multiplying the geometric constants R_3 and S_3 of the bearings with steel rolling elements by a factor 0,41, i.e. 0,41 R_3 and 0,41 S_3, respectively.

Hybrid deep groove ball bearings in high-speed applications are usually preloaded axially. Under these conditions, hybrid deep groove ball bearings behave like angular contact ball bearings with a similar reduced frictional moment.