The Design of Rolling Bearing Mountings

PDF 2/8:
Prime motors, electric motors
Power engineering
Metalworking machines

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The Design of Rolling Bearing Mountings

Design Examples covering Machines, Vehicles and Equipment

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This publication presents design examples covering various machines, vehicles and equipment having one thing in common: rolling bearings.

For this reason the brief texts concentrate on the rolling bearing aspects of the applications. The operation of the machine allows conclusions to be drawn about the operating conditions which dictate the bearing type and design, the size and arrangement, fits, lubrication and sealing.

Important rolling bearing engineering terms are printed in italics. At the end of this publication they are summarized and explained in a glossary of terms, some supplemented by illustrations.
Example Title

PRIME MOTORS, ELECTRIC MOTORS

1 Traction motor for electric standard-gauge locomotives ............... 2/8
2 Traction motor for electric commuter trains ......................... 2/8
3 Three-phase current standard motor .......................... 2/8
4 Electric motor for domestic appliances ..................... 2/8
5 Drum of a domestic washing machine ...................... 2/8
6 Vertical-pump motor .................................. 2/8
7 Mine fan motor .................................... 2/8

POWER ENGINEERING

8 Rotor of a wind energy plant ............. 2/8

METALWORKING MACHINES

Work spindles of machine tools .......... 2/8

9 Drilling and milling spindle ............. 2/8
10 NC-lathe main spindle .................. 2/8
11 CNC-lathe main spindle ................. 2/8
12 Plunge drilling spindle ................. 2/8
13 High-speed motor milling spindle .... 2/8
14 Motor spindle of a lathe ................. 2/8
15 Vertical high-speed milling spindle .... 2/8
16 Bore grinding spindle ................. 2/8
17 External cylindrical grinding spindle .. 2/8
18 Surface grinding spindle ............... 2/8

Other bearing arrangements

19 Rotary table of a vertical lathe ........ 2/8
20 Tailstock spindle ......................... 2/8
21 Rough-turning lathe for round bars and pipes ................. 2/8
22 Flywheel of a car body press ............ 2/8
## 1 Traction motor for electric standard-gauge locomotives

### Operating data

Three-phase current motor supplied by frequency converter.
Nominal output 1,400 kW, maximum speed 4,300 min⁻¹ (maximum driving speed for transmissions with standard gear ratios is 200 km/h). One-end drive with herringbone gear pinion.

### Bearing selection, dimensioning

Collective loads which cover representative load cases for the motor torque, speeds, and percentages of time for the operating conditions in question, are used to determine bearing stressing.

<table>
<thead>
<tr>
<th>Load case</th>
<th>M_d (N·m)</th>
<th>n (min⁻¹)</th>
<th>q (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6,720</td>
<td>1,056</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2,240</td>
<td>1,690</td>
<td>34</td>
</tr>
<tr>
<td>3</td>
<td>1,920</td>
<td>2,324</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>3,200</td>
<td>2,746</td>
<td>42</td>
</tr>
<tr>
<td>5</td>
<td>2,240</td>
<td>4,225</td>
<td>6</td>
</tr>
</tbody>
</table>

The collective load is the basis for determining the average speeds (2,387 min⁻¹) and the average driving speed (111 km/h). For each of the load cases the tooth load acting on the pinion and the reaction loads from the bearings have to be calculated both for forward and backward motion (percentage times 50% each).

In addition to these forces, the bearings are subjected to loads due to the rotor weight, the unbalanced magnetic pull, unbalanced loads and rail shocks. Of these loads only the rotor weight, G_r, is known; therefore, it is multiplied by a supplementary factor f_γ = 1.5...2.5 – depending on the type of motor suspension. The bearing loads are determined from this estimated load. For the spring-suspended traction motor shown, a supplementary factor f_γ = 1.5 is used.

The bearing loads from weight and drive allow the resultant bearing loading to be determined by vector addition. In this example only the critical transmission-end bearing will be discussed. The attainable life \( L_{hna1...5} \) is determined for every load case using the formula \( L_{hna} = a_1 \cdot a_2 \cdot a_3 \cdot L_h \) [h], taking into account the operating viscosity \( \eta \) of the transmission oil at 120 °C, the rated viscosity \( \eta_1 \) as well as the factors K_1 and K_2.

The basic \( a_23 \) factor is between 0.8 and 3. The cleanliness factor is assumed to be 1. Then, \( L_{hna} \) is obtained using the formula:

\[
L_{hna} = \frac{100}{\frac{q_1}{L_{hna1}} + \frac{q_2}{L_{hna2}} + \frac{q_3}{L_{hna3}} + \ldots}
\]

When selecting the bearing it should be ensured that the nominal mileage is reached and that, due to the high speed, the drive-end bearing is not too large.

With the bearings selected the theoretical mileage of 2.5 million kilometers required by the customer can be reached.

A cylindrical roller bearing FAG NU322E.TVP2.C5.F1 serves as floating bearing at the drive end; an FAG 566513 with an angle ring HJ318E.F1 serves as the locating bearing.

The cylindrical roller bearing FAG 566513 is an NJ318E.TVP2.P64.F1, but its inner ring is 6 mm wider. The resulting axial clearance of 6 mm is required in order to allow the herringbone gearing on the pinion to align freely.

### Suffixes:

- **E** reinforced design
- **TVP2** moulded cage of glass fibre reinforced polyamide, rolling element riding
- **C5** radial clearance larger than C4
- **F1** FAG manufacturing and inspection specification for cylindrical roller bearings in traction motors which considers, among others, the requirements according to DIN 43283 "Cylindrical roller bearings for electric traction".
- **P64** tolerance class P6, radial clearance C4

### Machining tolerances

Drive end: shaft r5; end cap to M6

Opposite end: shaft n5; end cap to M6

The bearings are fitted tightly on the shaft due to the high load, which is sometimes of the shock type. This reduces the danger of fretting corrosion, particularly at the drive end.

### Bearing clearance

Due to the tight fits, the inner ring of the bearing is expanded and the outer ring with the roller-and-cage assembly is contracted. Thus the radial clearance of the bearing is reduced after mounting. It is further reduced during operation as the operating temperature of the inner ring is higher than that of the outer ring. For this reason bearings with an increased radial clearance (C4...C5) are mounted.
Lubrication, sealing

The drive-end bearing is lubricated, due to the high speeds, with transmission oil ISO VG 320 with EP additives. No sealing is required between pinion and bearing so that a shorter cantilever can be used, thus reducing the bearing loading. Flinger edges and oil collecting grooves prevent the oil from escaping in the direction of the coil.

The bearing at the opposite end is lubricated with a lithium soap base grease of NLGI penetration class 3 (FAG rolling bearing grease Arcanol L71V). The bearings should be relubricated after 400,000 kilometers or five years, respectively. Multiple labyrinths prevent contaminants from penetrating into the bearings.

1: Traction motor for electric standard-gauge locomotive
Traction motor for electric commuter trains

Operating data

Self-ventilated converter current motor, permanent power 200 kW at a speed of 1,820 min\(^{-1}\) (driving speed 72 km/h), maximum speed 3,030 min\(^{-1}\) (maximum driving speed 120 km/h), one-end drive with herringbone gear pinion.

Bearing selection, dimensioning

The operating mode of commuter train motor vehicles is characterized by the short distances between stops. The periodic operating conditions – starting, driving, braking – can be recorded on an operating graph representing the motor torque versus the driving time. The cubic mean of the motor torque and an average speed, which is also determined from the operating graph, form the basis for the rolling bearing analysis. The mean torque is about 90 % of the torque at constant power.

The bearing loads are calculated as for traction motors for standard-gauge locomotives (example 1). They are made up of the reaction loads resulting from the gear force on the driving pinion and a theoretical radial load which takes into account the rotor weight, the magnetic pull, unbalanced loads and rail shocks. This theoretical radial load applied at the rotor centre of gravity is calculated by multiplying the rotor weight by the supplementary factor \(f_r = 2\). The value 2 takes into account the relatively rigid motor suspension.

An overhung pinion provides the drive. At the pinion end a cylindrical roller bearing FAG NU320E.M1.P64.F1 is mounted as the floating bearing. At the commutator end a deep groove ball bearing FAG 6318M.P64.J20A very safely accommodates the thrust load resulting from the 7° helical gearing of the pinion, even at relatively high speeds.

Suffixes

- **E**  Maximum capacity
- **M, M1**  Machined brass cage, rolling element riding
- **P64**  Tolerance class P6; radial clearance C4
- **F1**  FAG manufacturing and inspection specification for cylindrical roller bearings in traction motors which takes into account, among others, the requirements of DIN 43283 "Cylindrical roller bearings for electric traction".
- **J20A**  Current insulation on the outer ring O.D.

Machining tolerances

For good support of the bearing rings, tight fits are provided:
- Cylindrical roller bearing: Shaft to n5; end cap to M6
- Deep groove ball bearing: Shaft to m5; end cap to K6

Bearing clearance

The tight fits and the high temperature due to the relatively high operating speed require an increased radial clearance C4 for the cylindrical roller bearing and the deep groove ball bearing.

Lubrication, sealing

The bearings are lubricated with FAG rolling bearing grease Arcanol L71V as for all traction motors. Relubrication is possible, and a grease valve is provided to protect against overlubrication.

Experience shows that relubrication intervals of 250,000 km or 5 years provide optimum life.

The bearings are sealed on both sides by multiple labyrinth (axially arranged passages).
Current insulation

Where converter current motors with an output of more than 100 kW are used, ripple voltages can be caused by magnetic asymmetries. As a result, an induced circuit is generated between rotor shaft and stator which can cause current passage damage in the bearing.

To interrupt the flow of current, one bearing (in this case the deep groove ball bearing) is provided with current insulation.

Current-insulated bearings feature an oxide ceramic coating on the outer ring O.D.s and faces.

2: Traction motor of an electric commuter train
Three-phase current standard motor

Operating data

Belt drive: Power 3 kW; rotor mass 8 kg; nominal speed 2,800 min⁻¹; size 100 L; totally enclosed fan-cooled according to DIN 42673, sheet 1 – design B3, type of protection IP44, insulation class F.

Bearing selection

Low-noise bearings in a simple, maintenance-free arrangement should be provided. These requirements are best met by deep groove ball bearings. In DIN 42673, the shaft-end diameter specified for size 100 L is 28 mm. Consequently, a bore diameter of 30 mm is required. In this case a bearing of series 62 was selected for both bearing locations, i.e. an FAG 6206.2ZR.C3.L207. They guide the rotor shaft both at the drive side and at the ventilating side. The spring at the drive side provides clearance-free adjustment of the bearings and accommodates opposing axial loads on the rotor shaft. By adjusting the deep groove ball bearings to zero clearance the adverse influence of bearing clearance on noise behaviour is eliminated.

Bearing dimensioning

The calculation of the bearings for this motor differs somewhat from the usual approach. As not even the motor manufacturer knows the amount of load at the shaft end, the permissible radial loading is indicated in the motor catalogues. To determine the radial load carrying capacity, the drive-side deep groove ball bearing is calculated. The calculation is based on an attainable life $L_{bhna}$ of 20,000 h and a basic $a_{2311}$ value of 1.5. In addition, the rotor weight, the unilateral magnetic pull and the unbalanced load have to be taken into account. As the latter two criteria are not known the rotor weight is simply multiplied by a supplementary factor of $f_z = 1.5$.

With these values a permissible radial loading of 1 kN is calculated for the shaft-end middle. Since the operating load in most applications is lower than the admissible load, an attainable life $L_{bhna}$ of more than 20,000 hours is obtained. The life of electric motor bearings, therefore, is usually defined not by material fatigue but by the grease service life.

Suffixes

.2ZR Bearing with two shields
C3 Radial clearance larger than PN (normal)
L207 Grease filling with Arcanol L207

Machining tolerances

Shaft to j5; end cap bore to H6. The bore tolerance H6 ensures the slide fit required for free axial adjustment of both bearings.

Lubrication, sealing

The .2ZR design with shields on both bearing sides has been successful in small and medium-sized electric motors. The grease filling in these bearings is sufficient for their entire service life. Increased operating temperatures must be taken into consideration in the case in question due to the insulation class F provided. For this reason the FAG high-temperature grease Arcanol L207 is used. The shields prevent the grease from escaping and protect the bearings from contamination from the motor. Gap type seals protect the shaft opening at the drive side against dust and moisture. The requirements on insulation type IP44 are, therefore, met.
Electric motor for domestic appliances

Operating data

Power 30 W; speed 3,500 min⁻¹.

Bearing selection

Quiet running is the prime requirement for domestic appliance motors. The noise level of a motor is influenced by bearing quality (form and running accuracy), bearing clearance and the finish of the shaft and end cap bore.

Today, the quality of standard bearings already adequately meets the common noise requirements. Zero-clearance operation of the bearings is achieved by a spring washer lightly preloading the bearings in the axial direction.

The bearing seats on the shaft and in the end cap bores must be well aligned. To allow the spring washer to adjust the bearings axially, the outer rings have slide fits in the end caps.

A deep groove ball bearing FAG 626.2ZR is provided on the collector side, and an FAG 609.2ZR.L91 on the other side.

Suffixes

.2ZR Bearing with shields on both sides; they form a gap-type seal
L91 special grease filling (Arcanol L91)

Bearing dimensioning

The shaft diameter is usually dictated by the machine design, and as a result the bearings are sufficiently dimensioned with regard to fatigue life. Fatigue damage hardly ever occurs; the bearings reach the required life of between 500 and 2,000 hours.

Machining tolerances

Shaft to j5; end cap bore to H5

The bore tolerance H5 provides the slide fit required to permit free axial alignment of both bearings.

Sealing, lubrication

Grease lubrication with lithium soap base grease of consistency number 2 with an especially high degree of cleanliness. It is characterized by its low friction. The overall efficiency of this motor is considerably influenced by the frictional moment of the ball bearings.

The bearings with shields (.2ZR design) are prelubricated with grease, i.e. regreasing is not required. The gap-type seal formed by the shields offers adequate protection against contamination under normal ambient conditions.
Drum of a domestic washing machine

Operating data

Capacity 4.5 kg dry mass of laundry
(weight G_w = 44 N);
Speeds: when washing 50 min⁻¹
when spinning after prewash cycle 800 min⁻¹
when dry spinning 1,000 min⁻¹

Bearing selection

The domestic washing machine is of the front loading type. The drum is overhung and pulley-driven.
Bearing selection depends on the journal diameter which is determined by rigidity requirements, and also on the weight and unbalanced loads. Very simplified data is assumed for bearing load determination, on which the bearing dimensions are based, since loads and speeds are variable.

Domestic washing machines generally have several, partly automatic, washing cycles with or without spinning. During the actual washing cycle, i.e. a cycle without spinning, the drum bearings are only lightly loaded by the weight resulting from drum and wet laundry. This loading is unimportant for the bearing dimensioning and is thus neglected. The opposite applies to the spinning cycle: Since the laundry is unevenly distributed around the drum circumference, an unbalanced load arises which, in turn, produces a large centrifugal force. The bearing dimensioning is based on this centrifugal force as well as on the weights of the drum, G_T, and the dry laundry, G_w. The belt pull is generally neglected.

The centrifugal force is calculated from:

\[ F_Z = m \cdot r \cdot \omega^2 \ [N] \]

where

\[ m = \frac{G_U}{g} \ [N \cdot s^2/m] \]

\[ G_U \] Unbalanced load [N], 10...35 % of the dry laundry capacity is taken as unbalanced load.
\[ g \] Acceleration due to gravity = 9.81 m/s²
\[ r \] Radius of action of unbalanced load [m]
\[ \omega \] Angular velocity = \( \pi \cdot n / 30 \) [s⁻¹]
\[ n \] Drum speed during spinning [min⁻¹]

The total force for determination of the bearing loads thus is: 
\[ F = F_Z + G_T + G_W \ [N] \]
This load is applied to the washing drum centre.

The bearing loads are:

Bearing A
\[ F_{rA} = F \cdot \frac{l_2}{a} \ [N] \]

Bearing B
\[ F_{rB} = F \cdot \frac{l_1}{a} \ [N] \]

Bearing dimensioning

The bearings for domestic washing machines are dimensioned for an index of dynamic stressing \( f_L = 0.85...1.0 \).
These values correspond to a nominal life of 300...500 hours of spinning.
In the example shown a deep groove ball bearing FAG 6306.2ZR.C3 was selected for the drum side and a deep groove ball bearing FAG 6305.2ZR.C3 for the pulley side.
The bearings have an increased radial clearance C3 and are sealed by shields (.2ZR) at both sides.

Machining tolerances

Due to the unbalanced load G_U, the inner rings are subjected to point load, the outer rings to circumferential load. For this reason, the outer rings must have a tight fit in the housing; this is achieved by machining the housing bores to M6. The fit of the inner rings is not as tight; drum journal to h5. This ensures that the floating bearing is able to adjust in the case of thermal expansion. A loose fit also simplifies mounting.

Lubrication, sealing

The bearings, sealed at both sides, are prelubricated with a special grease, sufficient for the bearing service life. There is an additional rubbing-type seal at the drum side.
5: Drum mounting of a domestic washing machine
Operating data

Rated horsepower 160 kW; nominal speed 3,000 min⁻¹; Rotor and pump impeller mass 400 kg; pump thrust 9 kN, directed downwards; type V1.

Bearing selection

The selection of the bearings is primarily based on the main thrust, which is directed downwards. It is made up of the weight of the rotor and and pump impeller (4 kN), the pump thrust (9 kN) and the spring preload (1 kN). When the motor idles the pump thrust may be reversed so that the bearings have, briefly, to accommodate an upward axial load of 4 kN, as well. The radial loads acting on the bearings are not exactly known. They are made up by the unbalanced magnetic pull and potential unbalanced loads from the rotor and pump impeller. However, field experience shows that these loads are sufficiently taken into account by taking 50% of the rotor and pump impeller mass, which in this case is 2 kN.

In the example shown, the supporting bearing is an angular contact ball bearing FAG 7316B.TVP which has to accommodate the main thrust. To ensure that no radial force acts on the bearing this part of the housing is radially relieved to clearance fit E8.

In normal operation, the deep groove ball bearing FAG 6216.C3 takes up only a light radial load and the axial spring preload; in addition, the thrust reversal load of the idling motor has to be accommodated. As a result, the rotor is vertically displaced in the upward direction (ascending distance) which is limited by the defined gap between deep groove ball bearing face and end cap. To avoid slippage during the thrust reversal stage, the angular contact ball bearing is subjected to a minimum axial load by means of springs.

On the pump impeller side a cylindrical roller bearing FAG NU1020M1.C3 acts as the floating bearing. As it accommodates the unbalanced loads from the pump impeller both the inner and the outer ring are fitted tightly.

The cylindrical roller bearing design depends on the shaft diameter of 100 mm, which in turn is dictated by strength requirements. Due to the relatively light radial load, the lighter series NU10 was selected.

Machining tolerances

Cylindrical roller bearing: Shaft to m5; housing to M6
Deep groove ball bearing: Shaft to k5; housing to H6
Angular contact ball bearing: Shaft to k5, housing to E8

Lubrication

The bearings are lubricated with FAG rolling bearing grease Aracanol L71V and can be relubricated.

<table>
<thead>
<tr>
<th>Bearing Type</th>
<th>Shaft Fit</th>
<th>Housing Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floating bearing</td>
<td>m5</td>
<td>M6</td>
</tr>
<tr>
<td>Locating bearing</td>
<td>k5</td>
<td>H6</td>
</tr>
</tbody>
</table>

Replenishment quantity

- for the floating bearing 15 g
- for the locating bearing 40 g

The relubrication interval is 1,000 hours. The spent grease is collected in annular cover chambers provided below the bearing locations.
6: Rotor bearing arrangement of a vertical-pump motor
Mine fan motor

Operating data

Rated horsepower 1,800 kW; speed \( n = 750 \text{ min}^{-1} \); Axial load \( F_a = 130 \text{ kN} \); radial load \( F_r = 3.5 \text{ kN} \); the bearings are vertically arranged.

Bearing selection

The axial load of 130 kN is made up of the weight of the rotor and the two variable top and bottom fan impellers as well as the thrust of these fan impellers. They are supported by the upper thrust bearing.

The radial loads on vertical motors are only guiding loads. They are very small and generally result from the unbalanced magnetic pull and the potential rotor unbalanced load. In the example shown, the radial load per bearing is 3.5 kN. If the exact values are not known, these loads can be sufficiently taken into account, assuming that half the rotor weight acts as the radial load at the rotor centre of gravity.

The upper supporting bearing is a spherical roller thrust bearing FAG 29260E.MB. Radial guidance is ensured by a deep groove ball bearing FAG 16068M mounted on the same sleeve as the supporting bearing and accommodating the opposing axial loads on the rotor. Axial guidance is necessary for transporting and mounting as well as for motor idling. In this operating condition the counterflow of air can cause reversal of rotation and thrust. The axial displacement is limited to 1 mm in the upward direction so that the spherical roller thrust bearing does not lift off. Springs arranged below the housing washer (spring load 6 kN) ensure continuous contact in the bearings.

Radial guidance at the lower bearing position is provided by a deep groove ball bearing FAG 6340M; it is mounted with a slide fit as the floating bearing. Since it is only lightly loaded, it is preloaded with springs of 3 kN.

Bearing dimensioning

Spherical roller thrust bearing FAG 29260E.MB has a dynamic load rating of \( C = 1430 \text{ kN} \). The index of dynamic stressing \( f_L = 4.3 \) is calculated with the axial load \( F_a = 130 \text{ kN} \) and the speed factor for roller bearings 

\( f_n = 0.393 \) \( (n = 750 \text{ min}^{-1}) \). The nominal life \( L_h = 65,000 \text{ hours} \).

Based on the operating viscosity \( \nu \) of the lubricating oil (viscosity class ISO VG150) at approx. 70 °C, the rated viscosity \( \nu_1 \) and the factors \( K_1 \) und \( K_2 \), a basic value of about 3 is determined. The cleanliness factors is assumed to be 1. The attainable life \( L_{hna} \) of the thrust bearing is longer than 100,000 hours and the bearing is therefore sufficiently dimensioned. The two radial bearings are also sufficiently dimensioned with the index of dynamic stressing \( f_L > 6 \).

Machining tolerances

**Upper bearing location**

Spherical roller thrust bearing: Shaft to k5; housing to E8

Deep groove ball bearing: Shaft to k5; housing to H6

**Lower bearing location**

Deep groove ball bearing: Shaft to k5; housing to H6

Lubrication, sealing

**Thrust and radial bearings** at the upper bearing location are oil-lubricated.

The spherical roller thrust bearing runs in an oil bath and, due to its asymmetrical design, provides automatic circulation from the inner to the outer diameter. A tapered oil feeder and angled oilways supply the upper bearing. A retaining and a flinger ring ensure oil supply during start-up. The lower bearing is grease-lubricated with provision for relubrication and a grease valve. Both bearing locations are labyrinth-sealed.
7: Rotor bearing arrangement of a mine fan motor
Wind energy plants are among the alternative and environmentally friendly energy sources. Today, they generate powers of up to 3,200 kW. There are horizontal-rotor systems and vertical-rotor systems. The wind energy plant WKA60 is 44 meters high and features a three-blade horizontal rotor with a diameter of 60 m.

Operating data

Nominal speed of the three-blade rotor = 23 min⁻¹; gear transmission ratio i = 1:57.4; electrical power 1,200 kW at a nominal rotor speed of the generator of n = 1,320 min⁻¹.

Bearing selection

A service life of 20 years was specified. To support the overhung blade rotor, spherical roller bearings FAG 231/670BK.MB (dimensions 670 x 1,090 x 336 mm) were selected for the locating bearing location and FAG 230/900BK.MB (dimensions 900 x 1,280 x 280 mm) for the floating bearing location.

Bearing dimensioning

The recommended value for dimensioning the main bearings of wind energy plants is P/C = 0.08...0.15. The varying wind forces, causing vibrations, make it difficult to exactly determine the loads to be accommodated by the bearings. A nominal life of Lₙ > 130,000 h was specified. For this reason, the mean equivalent load is, as a rule, determined on the basis of several load cases with variable loads, speeds and percentage times. The locating bearing of the WKA60 plant is subjected to radial loads of Fᵣ = 400...1,850 kN and thrust loads of Fₜ = 60...470 kN. The floating bearing may have to accommodate radial loads of Fᵣ = 800...1,500 kN.

For the locating bearing, the radial and axial loads to be accommodated yield a mean equivalent dynamic load of P = 880 kN. For the bearing FAG 231/670BK.MB with a dynamic load rating of C = 11,000 kN this yields a load ratio of P/C = 880/11,000 = 0.08.

The floating bearing FAG 230/900BK.MB accommodates a mean radial force of Fᵣ = P = 1,200 kN. With a dynamic load rating of 11,000 kN a load ratio of 1,200/11,000 = 0.11 is obtained.

The life values calculated for the normally loaded spherical roller bearings (in accordance with DIN ISO 281) are far above the number of hours for 20-year continuous operation.

Mounting and dismounting

To facilitate mounting and dismounting of the bearings, they are fastened on the shaft by means of hydraulic adapter sleeves FAG H31/670HGJS and FAG H30/900HGS. Adapter sleeves also allow easier adjustment of the required radial clearance.

The bearings are supported by one-piece plunger block housing of designs SUB (locating bearing) and SUC (floating bearing). The housings are made of cast steel and were checked by means of the finite-element method.

Machining tolerances

The withdrawal sleeve seats on the rotor shaft are machined to h9 and cylindricity tolerance IT5/2 (DIN ISO 1101).

The bearing seats in the housing bore are machined to H7; this allows the outer ring of the floating bearing to be displaced.

Lubrication, sealing

The bearings are lubricated with a lithium soap base grease of penetration class 2 with EP additives (FAG rolling bearing grease Arcanol L186V). The housings are sealed on both sides by means of a double felt seal. A grease collar around the sealing gap prevents ingress of dust, dirt and, possibly, splash water.

Wind energy plant, schematic drawing
8: Rotor shaft bearings of a wind energy plant
The heart of every machine tool is its main or work spindle and its work spindle bearings. The main quality characteristics of the spindle-bearing system are cutting volume and machining precision. Machine tools are exclusively fitted with rolling bearings of increased precision; mainly angular contact ball bearings and spindle bearings (radial angular contact ball bearings with contact angles of 15° and 25°, respectively), double-direction angular contact thrust ball bearings, radial and thrust cylindrical roller bearings and, occasionally, tapered roller bearings.

Depending on the performance data required for a machine tool, the spindle bearing arrangement is designed with ball or roller bearings based on the following criteria: rigidity, friction behaviour, precision, speed suitability, lubrication and sealing.

Out of a multitude of possible spindle bearing arrangements for machine tools a few typical arrangements have proved to be particularly suitable for application in machine tools (figs. a, b, c).

**Dimensioning**

Usually, a fatigue life calculation is not required for the work spindles since, as a rule, to achieve the required spindle and bearing rigidity, bearings with such a large bore diameter have to be selected that, with increased or utmost cleanliness in the lubricating gap, the bearings are failsafe. For example, the index of dynamic stressing $f_L$ of lathe spindles should be $3...4.5$; this corresponds to a nominal life of $L_h = 15,000...50,000$ h.

Example: The main spindle bearing arrangement of a CNC lathe (fig. a) is supported at the work end in three spindle bearings B7020E.T.P4S.UL in tandem-O-arrangement (contact angle $\alpha_0 = 25^\circ$, $C = 76.5$ kN, $C_0 = 76.5$ kN). At the drive end, the belt pull is accommodated by a double-row cylindrical roller bearing NN3018ASK.M.SP. The cutting forces cause 50% each of the axial reaction forces for the two tandem-arranged spindle bearings. The front bearing at the work end accommodates 60% of the radial forces. It is loaded with $F_r = 5$ kN, $F_a = 4$ kN at $n = 3,000$ min$^{-1}$.

If the bearings are lubricated with the lithium soap base grease FAG Arcanol L74V (base oil viscosity 23 mm$^2$/s at 40 °C), an operating viscosity of $\nu = 26$ mm$^2$/s will be obtained at an operating temperature of 35 °C. With the mean bearing diameter $d_m = 125$ mm and the speed $n = 3,000$ min$^{-1}$ a rated viscosity of $\nu_1 = 7$ mm$^2$/s is obtained.

This yields a viscosity ratio $\kappa = \nu/\nu_1 = 4$; i.e. the rolling contact areas are fully separated by a lubricant film.

With $\kappa = 4$, a basic $a_{23II}$ factor of 3.8 is obtained from the $a_{23}$ diagram. Since the bearings, as a rule, are relatively lightly loaded ($f_\tau > 8$), a very good cleanliness factor ($s = $ infinite) is obtained with increased ($V = 0.5$) and utmost ($V = 0.3$) cleanliness. Consequently, the factor $a_{23}$ ($a_{23} = a_{23II} \cdot s$), and thus the attainable life ($L_{h\infty} = a_1 \cdot a_{23} \cdot L_h$) becomes infinite; the bearing is failsafe.

So, as long as $f_\tau \geq 8$ and the main spindle bearings are lubricated well ($\kappa \geq 4$), only the cleanliness in the lubricating gap determines whether the bearing is failsafe or not.
### Drilling and milling spindle

#### Operating data

Input power 20 kW; range of speed $11...2,240 \text{ min}^{-1}$.

#### Bearing selection

Radial and axial forces are accommodated separately. The radial bearings are double-row cylindrical roller bearings – an FAG NN3024ASK.M.SP at the work end and an FAG NN3020ASK.M.SP at the opposite end. The double-direction angular contact thrust ball bearing FAG 234424M.SP guides the spindle in axial direction. This bearing has a defined preload and adjustment is, therefore, not required.

#### Lubrication, sealing

Circulating oil lubrication. The labyrinth seal at the work end consists of ready-to-mount, non-rubbing sealing elements. The inner labyrinth ring retains the lubricating oil, the outer labyrinth ring prevents the ingress of cutting fluid.

#### Machining tolerances

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Form tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical roller bearing</td>
<td>Shaft, tapered</td>
<td>Taper 1:12</td>
<td>IT1/2</td>
<td>IT1</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>K5</td>
<td>IT1/2</td>
<td>IT1</td>
</tr>
<tr>
<td>Angular contact thrust bearing</td>
<td>Shaft</td>
<td>h5</td>
<td>IT1/2</td>
<td>IT1</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>K5</td>
<td>IT1/2</td>
<td>IT1</td>
</tr>
</tbody>
</table>

Machining of the housing bore is simplified in that the nominal outside diameters of the radial and thrust bearings are the same. The O.D. tolerance of the angular contact thrust ball bearing is such as to provide a loose fit in the housing.
10 NC-lathe main spindle

Operating data

Input power 27 kW; maximum spindle speed 9,000 min⁻¹.

Main spindle bearings do not normally fail due to material fatigue but as a result of wear; the grease service life is decisive.

Bearing selection

The main requirements on this bearing arrangement are an extremely good speed suitability, rigidity, and accurate guidance of the work spindle. At the work end, a spindle bearing set FAG B7017C.T.P4S.DTL in tandem arrangement is provided; at the drive end, a spindle bearing set FAG B71917C.T.P4S.DTL in tandem arrangement.

The bearings are lightly preloaded (UL) and have an increased precision (P4S).

The arrangement has no floating bearing; it is a rigid locating bearing system. Both bearing groups together form an O arrangement.

FAG spindle bearings of universal design are intended for mounting in X, O or tandem arrangement in any arrangement. When mounting in X or O arrangement a defined preload results. The light preload UL meets the normal requirements.

The original preload remains in the bearings due to outer and inner spacer sleeves of identical lengths. With a good bearing distance, the axial and radial heat expansions of the work spindle compensate each other so that the bearing preload remains unchanged under any operating condition.

Bearing dimensioning

The size of the bearings is primarily based on the spindle rigidity required, i.e. on the largest possible spindle diameter. The fatigue life of the bearings is taken into account for dimensioning but it does not play a dominating role in practice.

Lubrication, sealing

The bearings are greased for life with the FAG rolling bearing grease Arcanol L74V and about 35% of the cavity is filled.

Sealing is provided by labyrinth seals with defined gaps.

Machining tolerances

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Form tolerance (DIN ISO 1101)</th>
<th>Axial run-out tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle bearings</td>
<td>Shaft</td>
<td>+5/-5 µm</td>
<td>1.5 µm</td>
<td>2.5 µm</td>
</tr>
<tr>
<td>Drive end/work end</td>
<td>Housing</td>
<td>+2/+10 µm</td>
<td>3.5 µm</td>
<td>5 µm</td>
</tr>
</tbody>
</table>

1: NC-lathe main spindle
Apart from the Hertzian contact pressure, the *service life* of the bearings is mainly dictated by the *grease service life*. Main spindle bearings do not normally fail due to material fatigue but as a result of *wear*.

**Bearing selection**

The bearings must accurately guide the spindle radially and axially and be very rigid. This is achieved by selecting as large a shaft diameter as possible and a suitable bearing arrangement. The bearings are preloaded and have an increased precision.

At the work end a spindle bearing set FAG B7018E.T.P4S.TBTL in *tandem-O-arrangement* with a light preload is mounted as locating bearing.

At the drive end there is a single-row cylindrical roller bearing FAG N1016K.M1.SP as floating bearing.

This bearing arrangement is suitable for high speeds and for high cutting capacities.

**Bearing dimensioning**

The bearing size is primarily based on the spindle rigidity required, i.e. on the spindle diameter. The *fatigue life* of the bearings is taken into account for dimensioning but it does not play a dominating role in practice.

**Bearing clearance**

FAG spindle bearings of *universal design* are intended for mounting in X, O or *tandem arrangement* in any arrangement. When mounting in X or O arrangement a set preload results. The light preload UL meets the normal requirements.

The cylindrical roller bearing is adjusted with almost zero *radial clearance* by axially pressing the tapered inner ring onto the spindle.

**Lubrication, sealing**

The bearings are greased for life with the FAG rolling bearing *grease Arcanol L74V*.

Approximately 35% of the spindle bearing cavity and approximately 20% of the cylindrical -roller bearing cavity is filled with *grease*.

*Sealing* is provided by a labyrinth with set narrow radial gaps.

**Machining tolerances**

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Form tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle bearings</td>
<td>Shaft</td>
<td>+5/–5 µm</td>
<td>1.5 µm</td>
<td>2.5 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>–4/+8 µm</td>
<td>3.5 µm</td>
<td>5 µm</td>
</tr>
<tr>
<td>Cylindrical roller bearings</td>
<td>Shaft, tapered</td>
<td>Taper 1:12</td>
<td>1.5 µm</td>
<td>2.5 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>–15/+3 µm</td>
<td>3.5 µm</td>
<td>5 µm</td>
</tr>
</tbody>
</table>
Plunge drilling spindle

Operating data
Input power 4 kW; maximum spindle speed 7,000 min⁻¹.

Bearing selection
Accurate axial and radial guidance of the drilling spindle is required. Consequently, bearing selection is based on the axial loads to be accommodated while providing the greatest possible axial rigidity. Another criterion is the available space which, e.g. in the case of multip spindle cutter heads, is limited.

Work end:
1 spindle bearing set FAG B71909E.T.P4S.TTL (three bearings mounted in tandem arrangement)

Drive end:
1 spindle bearing set FAG B71909E.T.P4S.DTL (two bearings mounted in tandem arrangement).

The two bearing sets can also be ordered as a single set of five:
FAG B71909E.T.P4S.PBCL (tandem pair mounted against three tandem-arranged bearings in O arrangement, lightly preloaded). This bearing arrangement includes no floating bearing; it forms a rigid locating bearing system.

Bearing dimensioning
The bearing size is based on the spindle rigidity required, i.e. on as large a spindle diameter as possible.

Bearing clearance
FAG spindle bearings of universal design are intended for mounting in X, O or tandem arrangement in any arrangement. When mounting in X or O arrangement, a set preload results. The light preload UL meets the normal requirements.

The original preload remains in the bearings due to outer and inner spacer sleeves of identical lengths. With a good bearing distance, the axial and radial heat expansions of the work spindle compensate each other so that the bearing preload remains unchanged under any operating condition.

Lubrication, sealing
The bearings are greased for life with the FAG rolling bearing grease Arcanol L74V and about 35 % of the cavity is filled.
Sealing is provided by labyrinth seals with a collecting groove and a drain hole where a syphon may be provided.

Machining tolerances

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Form tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle bearing (drive/work end)</td>
<td>Shaft</td>
<td>+3.5/–3.5 µm</td>
<td>1 µm</td>
<td>1.5 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>–3/+5 µm</td>
<td>2 µm</td>
<td>3 µm</td>
</tr>
</tbody>
</table>
Operating data

Input power 11 kW;  
maximum spindle speed 28,000 min⁻¹.

Bearing selection

The bearings must be suitable for very high speeds and  
for the specific thermal operating conditions in a mo-
tor spindle. Hybrid spindle bearings with ceramic balls  
are particularly suitable for this application.  
Milling spindles must be guided extremely accurately  
both in the axial and in the radial direction.

Work end:  
1 spindle bearing set FAG HC7008E.T.P4S.DTL in  
tandem arrangement.  

Drive end:  
1 spindle bearing set FAG HC71908E.T.P4S.DTL in  
tandem arrangement.

The bearing pairs at drive end and work end are  
mounted in O arrangement and elastically adjusted by  
means of springs (spring load 300 N), corresponding  
to a medium preload. The bearing pair at the drive end  
is mounted on a sleeve which is supported on a linear  
ball bearing with zero clearance so that axial length  
variations of the shaft can be freely compensated for.

Bearing dimensioning

Bearing size and bearing arrangement are selected on  
the basis of the specified speed and on the spindle  
diameter.  
Two other factors that have to be taken into account  
are the heat generated by the motor, which causes a  
major temperature difference between the inner ring  
and the outer ring of the bearing, and the ring expan- 
sion which makes itself felt by the centrifugal force re-
sulting from the high speed. In a rigid bearing arrange-
ment, this would considerably increase the preload.  
Due to the spring preload, both these influences are  
easily compensated for. As a result, the contact pres-
sure in the rolling contact area of the bearing is rela-
tively low (p₀ ≤ 2,000 N/mm²), and the bearings are  
failsafe. Consequently, the service life of the bearings is  
ddictated by the grease service life.

Lubrication, sealing

The bearings are lubricated with rolling bearing grease  
Arcanol L207V which is particularly suitable for the  
greater thermal stressing and for high speeds.  
To protect the grease from contamination, and conse-
quently to increase the grease service life, the bearings  
are sealed by labyrinths consisting of a gap-type seal  
with flinger grooves and a collecting groove.

Machining tolerances

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Form tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle bearing (drive/work end)</td>
<td>Shaft</td>
<td>+6/+10 µm</td>
<td>1 µm</td>
<td>1.5 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>−3/+5 µm</td>
<td>2 µm</td>
<td>3 µm</td>
</tr>
</tbody>
</table>

13: Bearing arrangement of a high-speed motor milling spindle
Motor spindle of a lathe

Operating data

Input power 18 kW; maximum spindle speed 4,400 min⁻¹.

Bearing selection

The bearings must be very rigid and accurately guide the spindle in the radial and axial direction. This is achieved by selecting as large a shaft diameter as possible and a suitable bearing arrangement. The bearings are preloaded and have an increased precision. Also, the specific thermal conditions found in a motor bearing arrangement have to be taken into account.

Work end: 1 spindle bearing set
FAG B7024E.T.P4S.QBCL (tandem-O-tandem arrangement) as locating bearing

Opposite end: 1 cylindrical roller bearing
FAG N1020K.M1.SP as floating bearing.

Bearing dimensioning

As the bearing size primarily depends on the spindle rigidity (larger spindle diameter) bearing sizes are obtained whose load carrying capacity is more than adequate. Consequently, the service life of the bearings is primarily dictated by the grease service life.

Bearing clearance

The spindle bearings are mounted with a light preload. The cylindrical roller bearing is adjusted to a radial clearance of a few µm by axially pressing the tapered inner ring onto the tapered shaft seat and reaches the required zero clearance at operating temperature.

Lubrication, sealing

The bearings are lubricated for life with the rolling bearing grease Arcanol L207V. This grease is particularly suitable for increased temperatures and high speeds. Approximately 35 % of the spindle bearing cavity and approximately 20 % of the cylindrical-roller bearing cavity is filled with grease.

Sealing is provided by a stepped labyrinth with collecting grooves and drain holes. A gap-type seal protects the cylindrical roller bearing from external contamination.

Machining tolerances

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Form tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle bearing</td>
<td>Shaft</td>
<td>-5/+5 µm</td>
<td>1.5 µm</td>
<td>2.5 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>-4/+10 µm</td>
<td>3.5 µm</td>
<td>5 µm</td>
</tr>
<tr>
<td>Cylindrical roller bearing</td>
<td>Shaft, tapered</td>
<td>1:12</td>
<td>1.5 µm</td>
<td>2.5 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>-15/+3 µm</td>
<td>3.5 µm</td>
<td>5 µm</td>
</tr>
</tbody>
</table>
Operating data

Input power 2.6/3.14 kW;
Nominal speed 500...4,000 min⁻¹.

Bearing selection

The bearings must operate reliably over the entire speed range from 500 to 4,000 min⁻¹. For example, the spindle must be rigidly guided at 500 min⁻¹ under heavy loads both in the radial and axial direction. On the other hand, at the maximum speed of 4,000 min⁻¹, the bearing temperature must not be so high as to impair accuracy.

At the milling spindle work end a spindle bearing set FAG B7014E.T.P4S.TBTM are mounted in tandem-O-arrangement with a medium preload. The bearing group is preloaded with 1.9 kN by means of a nut and a spacer sleeve.

The deep groove ball bearing FAG 6211TB.P63 guides the spindle at the drive end. To ensure clearance-free operation this bearing is lightly preloaded by means of Belleville spring washers.

Bearing dimensioning

Milling spindles must be resistant to deflection and torsion. This requirement dictates the spindle diameter and the bearing size. The required bearing rigidity is obtained by the chosen bearing arrangement and preload. The two angular contact ball bearings arranged at the upper drive end accommodate the driving forces.

Machining tolerances

<table>
<thead>
<tr>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Cylindricity tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>js4</td>
<td>IT1/2</td>
<td>IT1</td>
</tr>
<tr>
<td>Housing (work end)</td>
<td>J55</td>
<td>IT2/2</td>
<td>IT2</td>
</tr>
<tr>
<td>Housing (drive end)</td>
<td>H6</td>
<td>IT3/2</td>
<td>IT3</td>
</tr>
</tbody>
</table>

Lubrication, sealing

The bearings are grease lubricated (FAG rolling bearing grease Arcanol L74V).
A gap-type seal with oil splash ring and collecting grooves protect the spindle bearings from contamination.
Operating data

Input power 1.3 kW; spindle speed 16,000 min⁻¹.
The spindle is radially loaded by the grinding pressure.
The load depends on grinding wheel quality, feed and depth of cut.

Bearing selection

Due to the high speeds required during bore grinding, the spindle speeds must also be high. Sufficient rigidity and accurate guidance, especially in axial direction, are also required. The demands for high speed and high rigidity can be met with spindle bearings. As the spindle requires primarily a high radial rigidity, it is advisable to provide bearings with a contact angle of 15° (design C).

At the work end and at the drive end there is one spindle bearing set FAG B7206C.T.P4S.DTL in tandem arrangement each. The load is equally shared by these O arranged tandem bearing pairs. For this purpose the spacer rings must be identical in width and also flush ground.

The bearings are lightly preloaded by a coil spring for clearance-free operation under all operating conditions. The preload increases the rigidity of the bearing arrangement. It is, however, limited by the permissible bearing temperature and varies between 300 and 500 N depending on the spindle application.

The spindle diameter, which determines the bearing size, is based on the required rigidity.

Lubrication, sealing

Grease lubrication for high-speed bearings (FAG rolling bearing grease Arcanol L74V). The bearings are lubricated for life during mounting and therefore no relubrication is required.

The high-speed bearings require the use of non-rubbing seals, in this case labyrinth seals.

Machining tolerances

<table>
<thead>
<tr>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Cylindricity tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>js3</td>
<td>IT0/2</td>
<td>IT0</td>
</tr>
<tr>
<td>Housing (drive end)</td>
<td>+2/+6 µm</td>
<td>IT1/2</td>
<td>IT1</td>
</tr>
<tr>
<td>Housing (work end)</td>
<td>−1/+3 µm</td>
<td>IT1/2</td>
<td>IT1</td>
</tr>
</tbody>
</table>

16: Bearing arrangement of a bore grinding spindle
External cylindrical grinding spindle

Operating data

Input power 11 kW; speed \( n = 7,500 \text{ min}^{-1} \); running accuracy: radially 3 µm, axially 1 µm.

Bearing selection

During external cylindrical grinding a high cutting capacity is required (for rough grinding) and a high standard of form and surface quality (for fine grinding). A high degree of rigidity and running accuracy as well as good damping and speed suitability form the main criteria for the bearing arrangement. These requirements are met by precision bearings. Sealed universal spindle bearings with small steel balls (HSS) are used:

- at the work end: 1 spindle bearing set
  FAG HSS7020C.T.P4S.QBCL in double-\( O \) arrangement as locating bearing
- at the drive end: 1 spindle bearing set
  FAG HSS7020C.T.P4S.DBL in \( O \) arrangement as floating bearing

Where even higher speeds have to be accommodated, it is advisable to use sealed hybrid spindle bearings HCS with small ceramic balls (lower centrifugal forces).

Bearing dimensioning

The required spindle diameter or the specified outside diameter of the quill determines the bearing size. The contact angle of 15° is suitable for high radial rigidity.

Damping and running accuracy are improved by arranging four bearings at the work end.

Bearing clearance

All UL universal design bearings are lightly preloaded when mounted in \( O \) arrangement. Spacers improve the thermal conditions and provide a larger spread at the bearing location. To ensure that the defined bearing preload is not altered by the spacers, the latter must be identical in width and flush ground.

Lubrication, sealing

The sealed FAG HSS spindle bearings require no maintenance and are lubricated for life with the FAG rolling bearing grease Arcanol L74. Additional sealing is provided at the grinding wheel end by a labyrinth with defined narrow axial gaps of 0.3 ... 0.8 mm. A plain labyrinth seal is sufficient at the drive end.

Machining tolerances

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Form tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle bearing (work end)</td>
<td>Shaft</td>
<td>+3/–3 µm</td>
<td>1 µm</td>
<td>1.5 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>-3/+5 µm</td>
<td>2 µm</td>
<td>3.5 µm</td>
</tr>
<tr>
<td>Spindle bearing (drive end)</td>
<td>Shaft</td>
<td>+3/–3 µm</td>
<td>1 µm</td>
<td>1.5 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>+5/+13 µm</td>
<td>2 µm</td>
<td>3.5 µm</td>
</tr>
</tbody>
</table>

17: Bearing arrangement of an external cylindrical grinding spindle
Operating data

Grinding motor power 220 kW; maximum speed 375 min⁻¹; weight of spindle, rotor and grinding spindle head 30 kN; maximum grinding pressure 10 kN.

Bearing selection

The spindle is supported at the grinding spindle head by a double-row cylindrical roller bearing FAG NN3060ASK.M.SP. The thrust ball bearing FAG 51164MP.P5 arranged above this bearing absorbs the thrust component of the grinding pressure. The upper end of the spindle is fitted with a double-row cylindrical roller bearing FAG NN3044ASK.M.SP and a thrust ball bearing FAG 51260M.P6. The cylindrical roller bearing provides radial guidance; the thrust ball bearing carries the weight of the rotor, spindle, and spindle head. To increase axial rigidity this bearing is adjusted with Belleville spring washers against the lower thrust ball bearing.

Bearing dimensioning

Rigid spindle guidance in the radial direction is ensured by accurately dimensioned mating parts, tight fits of the rings, and a light preload of the cylindrical roller bearings. The inner rings are pushed along the tapered bearing seat until the roller-and-cage assembly runs under a light preload (5 µm). Surface finish and dimensional accuracy of the workpiece mainly depend on the axial rigidity of the spindle headstock and of the rotary table. Therefore, the rigidity of the thrust bearings is especially important. To increase the rigidity, the thrust bearings are preloaded to 40 kN by Belleville spring washers at the upper end of the spindle. Since the combined weight of spindle, rotor, and spindle head is 30 kN, the lower thrust bearing is preloaded to 10 kN. Rigid, clearance-free spindle guidance also in the axial direction is, therefore, guaranteed. The nominal rigidity is 2.5 kN/µm; the spindle deviates axially by only 4 µm with the maximum grinding pressure of 10 kN.

Lubrication, sealing

The headstock bearings are lubricated for life with FAG rolling bearing grease Arcanol L74V. A gap-type seal suffices at the upper spindle end since the headstock is protected by a cap. A shaft seal prevents grease from penetrating into the motor. The lower bearings are sealed at the motor end with a gap-type seal and at the spindle head with a gap-type seal preceded by a labyrinth.
Rotary table of a vertical lathe

Operating data

Input power 100 kW; speeds up to \( n = 200 \text{ min}^{-1} \); rotary table O.D. 2,000, 2,200 or 2,500 mm; maximum workpiece diameter 2,800 mm, maximum workpiece height 2,700 mm, maximum workpiece weight 250 kN; maximum radial and axial runout 5 µm.

Bearing selection

The face plate bearings must provide a high running accuracy and rigidity. As the thrust load predominates and eccentric load application causes a great tilting moment, a thrust ball bearing of increased precision (main dimensions 1,250 x 1,495 x 150 mm) is installed. Radial guidance is provided by an angular contact ball bearing of increased precision, FAG 7092MP.P5 (30° contact angle). Both bearings are preloaded against each other with 50 kN.

The high preload guarantees a high running accuracy while ensuring a high radial and axial moment or tilting rigidity and keeping internal heating relatively low. By taking special measures during mounting and after final grinding of the rotary table a maximum axial runout of 5 µm is obtained.

Machining tolerances

Thrust ball bearing: gearing to j5
Angular contact ball bearing: kingpin to j5/gearing to K6

Lubrication, sealing

The bearings have circulating oil lubrication. The oil is fed directly to the various bearings through oil feed ducts. After flowing through the bearings, the oil passes through a filter and into an oil collecting container from where it returns to the bearings. The labyrinth seal prevents the oil from escaping from the bearings and protects them from contamination.
Tailstock spindle

Operating data

Maximum speed \( n = 3,500 \text{ min}^{-1} \)

Bearing selection, dimensioning

The bearing arrangement must be particularly rigid and have a high load carrying capacity. Other requirements such as precision and high-speed suitability are met by bearings of precision design.

At the work end the high radial load is accommodated by a double-row cylindrical roller bearing FAG NN3014ASK.M.SP. The high axial load is accommodated at the opposite end by four angular contact ball bearings FAG 7210B.TVP.P5.UL. Three of these bearings are mounted in tandem arrangement; the fourth bearing is merely for axial counter guidance.

The maximum bearing O.D. is dictated by the size of the quill.

Bearing clearance

The cylindrical roller bearing with a tapered bore is preloaded with 2...3 µm by pressing the inner ring on to the tapered shaft seat (taper 1:12).

The angular contact ball bearings of universal design UL have a light preload in the \( O \) arrangement. The two spacers are identical in width and exclusively serve to provide a cavity which can accommodate the excess grease escaping from the bearings.

Lubrication, sealing

The bearings are lubricated for life with FAG rolling bearing grease Arcanol L135V. A labyrinth seal prevents dirt from penetrating into the bearings.

Machining tolerances

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Seat</th>
<th>Diameter tolerance</th>
<th>Form tolerance (DIN ISO 1101)</th>
<th>Axial runout tolerance of abutment shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical roller bearing</td>
<td>Shaft, tapered</td>
<td>Taper 1:12 −13 / +2 µm</td>
<td>1.5 µm</td>
<td>2 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td></td>
<td>2.5 µm</td>
<td>4 µm</td>
</tr>
<tr>
<td>Angular contact ball bearings</td>
<td>Shaft</td>
<td>−4 / +4 µm</td>
<td>1.5 µm</td>
<td>2 µm</td>
</tr>
<tr>
<td></td>
<td>Housing</td>
<td>−4 / +6 µm</td>
<td>2.5 µm</td>
<td>4 µm</td>
</tr>
</tbody>
</table>

20: Bearing arrangement of a tailstock spindle
Rough-turning lathes are used for particularly economical production of bars and pipes to tolerance class h9 with a wide range of diameters. In this process, the stationary round stock is moved against rotating lathe tools at a certain feed rate. In this machine four cutting tool carriages are attached to the circumference of the turrethead which are radially adjustable.

Operating data

Input power 75 kW; speed \( n = 300 \ldots 3,600 \text{ min}^{-1} \); material O.D. 11...85 mm; feed rate 1...40 m/min.

Bearing selection

The main bearing arrangement is formed by two spindle bearings FAG B7036E.T.P4S.UL and accommodates the cutting forces transmitted by the four cutting tools. The bearings are mounted in \( O \) arrangement and preloaded with 14.5 kN (2 % of \( C_0/Y_0 \)) by means of springs.

\( C_0 \) static load rating

\( Y_0 \) thrust factor (static loading)

Two angular contact ball bearings FAG 71848MP.P5.UL in \( O \) arrangement accommodate the guiding loads from the axially displaceable hollow cone in which the four tool carriages are radially guided and adjusted. These bearings are also adjusted against each other with a spring preload of 5 kN (1 % of \( C_0/Y_0 \)). Experience shows that with these preloads no slippage damage results, even if the rough-turning lathe is slowed down from 3,600 min\(^{-1}\) to zero within a second.

Machining tolerances

The inner rings of both bearings are subjected to circumferential loads and are fitted with a tolerance of js5. The bearing seats for the outer rings are machined to G6. The spring preload remains effective in all operating conditions as the expansion of the rotating parts due to the effects of heat and centrifugal force do not cause jamming of the outer rings in the housing.

Lubrication, sealing

The bearings are lubricated by oil injection lubrication with ISO VG 32 (32 mm\(^2\)/s at 40 °C). At 80 °C the oil has an operating viscosity of \( v = 8 \text{ mm}^2/\text{s} \). An elaborate labyrinth seal protects the bearings from the ingress of cutting fluid and chips (rubbed-off particles) and from oil escape.
Operating data

Input power 33 kW; flywheel speed 370 min⁻¹; radial load from flywheel weight and belt pull approximately 26 kN.

Bearing selection

Both rings must be tightly fitted to their mating parts due to the heavy loads and the circumferential load on the outer ring. Nevertheless, mounting and dismounting should be simple. These requirements can be met with cylindrical roller bearings. They feature a high load carrying capacity, and they are separable, i.e. inner and outer rings can be mounted separately.

The flywheel is supported on the hollow trunnion protruding from the press frame by two cylindrical roller bearings FAG NU1048M1A. The suffix M1A indicates that the bearings are fitted with an outer ring riding machined brass cage. Two angle rings HJ1048, one at each of the outer sides of the cylindrical roller bearings, are provided for axial location of the flywheel. Spacer J is arranged between the bearing inner rings and spacer A between the outer rings. Spacer J is 0.6 ± 0.2 mm longer than spacer A, which ensures adequate axial clearance. After the bearing has been mounted, the axial clearance is checked (minimum 0.4 mm).

Bearing dimensioning

The trunnion diameter, which is determined by the design, determines in turn the bearing size.

Machining tolerances

The outer rings are subjected to circumferential load and therefore require tight fits; the hub bore is machined to M6. The inner rings are point-loaded. The trunnion is machined to j5.

Bearing clearance

Calculations show that the radial clearance is reduced after mounting, due to outer ring contraction and inner ring expansion (probable interference), by only 20 µm from the value measurable prior to mounting (value indicated in table). Bearings of normal radial clearance (CN = 110...175 µm) can, therefore, be used.

Lubrication, sealing

Grease lubrication (FAG rolling bearing grease Arcanol L71V). Shaft seals prevent the ingress of dirt.
22: Flywheel bearing arrangement of a car body press