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Analysis of the influence of radial clearance variation between rows in cylindrical roller bearings of railway wheelsets on bearing life

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ABSTRACT

Cylindrical roller bearings used in railway wheelsets operate under high radial loads and dynamic conditions that significantly affect their internal load distribution and fatigue life. One of the key parameters influencing bearing performance is the radial internal clearance (RIC). In multi-row cylindrical roller bearing sets, even slight variations in RIC between individual rows can lead to uneven load sharing, localized stress concentrations, and accelerated fatigue damage. In this study, the influence of radial clearance variation between bearing rows on the bearing life of railway wheelset assemblies was analyzed. Calculations were performed using the ROMAX Spin software, which enables comprehensive bearing system life analyses in accordance with the ISO/TS 16281. The study evaluated how differences in operational clearance between bearing rows within the same axlebox, together with axle journal deflection and bearing housing stiffness, affect load distribution, contact pressure, and the resulting life of each bearing row as well as the overall system life. The results demonstrated that unequal radial clearances cause an uneven load transfer toward the stiffer rows, thereby reducing the overall bearing system life to that of the most heavily loaded row. Recommendations are provided for optimizing assembly tolerances and maintaining uniform operational clearance between rows to ensure reliable bearing performance and extended service life in railway applications.

Keywords: roller bearing, radial clearance, wheelsets, bearing life, railway, axlebox.

INTRODUCTION

The roller bearings used in railway wheelsets play a critical role in ensuring the safe and reliable operation of rail vehicles. Failures occurring within this system may lead to hazardous events classified as accidents or serious incidents. In Poland, damage to the axlebox assembly is the second most frequent cause of railway accidents and the incidents related to the technical condition of rolling stock, following failures of the braking system [1, 2, 15, 26, 27]. The increasing number of wheelset bearing failures is also highlighted in the most recent annual safety reports published by the Office of Rail Transport [28, 29]. For freight wagons, it is justified to classify wheelset rolling bearings as safety-critical components [2] in accordance with Commission Implementing Regulation (EU) 2019/779 and Directive (EU) 2016/798 on railway safety.

One of the most important parameters affecting the bearing life is the radial internal clearance (RIC), defined as the total possible relative displacement of the inner ring with respect to the outer ring in the radial direction when the bearing is not subject to external load. Depending on application requirements, bearings are produced in several clearance classes (C1, C2, CN, C3, C4, C5) as specified in ISO 5753-1. Class CN represents normal clearance, C1 and C2 represent reduced clearance, while C3 and higher classes represent increased clearance [11]. The operating radial clearance, i.e. the clearance under actual service conditions, depends not only on the manufactured clearance, but also on the fits between the inner ring and the axle journal, the outer ring and the axlebox housing, thermal expansion of the materials used, as well as the operating temperature.

The influence of radial clearance on load distribution and fatigue life has been studied, but without focusing on specific applications, such as railway wheelsets [3, 4, 8, 16, 18, 20–22, 24, 25, 32]. The research by Oswald, Zaretsky, Pawlowski, Warda, Chudzik and others confirms that the value of radial clearance has a significant influence on bearing performance. A slight negative clearance (preload) may be beneficial for fatigue life, whereas too small clearance increases stress concentrations at the roller edges. Excessive clearance, on the other hand, leads to non-uniform load sharing and reduced bearing life [3], [19]. When defining the required clearance for a specific application, the sensitivity of the bearing to misalignment should also be taken into account [31]. Research indicates that the optimal range of operating RIC depends on expected loading conditions and a geometry (profile drop) of raceways and rolling elements [30]. Operating radial clearance also affects the overall vibration level of the system [33].

Existing literature focuses mainly on the impact of clearance variation within a single bearing row or considers only the averaged clearance of a bearing set. There is a noticeable lack of studies addressing the influence of operating RIC variation specifically in the bearings used in railway wheelsets. Equally absent are works analyzing the impact of differences in radial clearance between individual rows of the same bearing set, or studies assessing how the arrangement of paired cylindrical roller bearings affects system life. This issue is not covered in historical ORE reports [17] nor in the actual standards governing the design and maintenance of railway wheelsets, such as EN 15313:2024 or EN 13260:2020 [5, 6].

In specialist publications devoted partially or entirely to the calculation of the service life of rolling bearings used in railway wheelsets, and intended as practical guidelines for this specific application [22, 24], the scenario in which two rows of bearings with different values of radial internal clearance are installed in the same axlebox is not considered. The methodologies presented in these publications are based on basic rating life calculations (L10) according to ISO 281 [10]. They omit not only the influence of variations in radial clearance, but also the effects of axle journal deflection, the stiffness of the axlebox bearing arrangement, and the misalignment resulting from these installation conditions. Only the extended calculation methodology defined in the ISO/TS specifications [12, 13] makes it possible to account accurately for these factors in the fatigue-life assessment of rolling bearings used in railway wheelsets.

OBJECTIVES AND SCOPE OF THE STUDY

Given the significant contribution of wheelset rolling bearing failures to railway safety incidents and the critical role these components play in the safe operation of rail vehicles, it is essential to examine how specific operating RIC affects bearing life. This article focused on an aspect that has so far been largely overlooked: the impact of asymmetric radial internal clearance between rows of cylindrical roller bearings installed within the same axlebox on the calculated life of each row and the system life.

Three main bearing types are used in railway applications: spherical roller bearings, cylindrical roller bearings, and tapered roller bearings. Spherical roller bearings, due to their susceptibility to internal sliding, are typically found in older designs. Modern rolling stock predominantly uses cylindrical or tapered roller bearings [23]. In tapered roller bearings, radial internal clearance is not defined separately for each row but results from the axial play of the bearing assembly, meaning that asymmetry between rows cannot be analyzed independently. For this reason, the present study focused exclusively on cylindrical roller bearings.

The objective of this study was to determine the extent to which asymmetry in radial internal clearance may cause uneven load sharing between individual rows, local stress concentrations, and premature fatigue damage.

The scope of the study includes the following tasks:

- Development of a detailed computational model in ROMAX Spin that accurately

reflects real operating and installation conditions, including axle journal deflection, axlebox housing stiffness, as well as the magnitude and direction of applied loads.
- Execution of multiple calculation scenarios with varying differences in radial internal clearance between the bearing rows.
- Determination of load distribution, contact pressures on the inner and outer ring raceways for each scenario.
- Calculation of the modified reference rating life according to ISO/TS 16281 for each bearing row as well as for the overall bearing system.
- Evaluation of the influence of clearance asymmetry on ring misalignment and the resulting changes in contact conditions.
- Formulation of recommendations on the pairing and installation of cylindrical roller bearings within a single axlebox, including identification of clearance combinations that enhance bearing life and system reliability.

This study extends previous research, which has mostly focused on individual bearings or average clearance values. The results may be applied in the design, maintenance, and overhaul of railway wheelsets equipped with multi-row cylindrical roller bearings, and in the development of maintenance documentation and inspection procedures.

CALCULATION MODEL, BOUNDARY CONDITIONS AND LOAD CASES

All analyses in this study were performed using the advanced ROMAX Spin software developed by Hexagon Manufacturing Intelligence GmbH. ROMAX provides comprehensive tools for modeling and analyzing drivetrain components, gear systems, and rotating machinery. The Spin module enables highly detailed simulations of rolling bearings, taking into account micro and macro geometry, boundary conditions, and operating loads, thereby allowing the calculation of bearing life under realistic service conditions [9].

The analyses were carried out for the most common wheelset configuration used in railway vehicles, in which the bearings are mounted on the axle journal outside the wheel (outboard design). This arrangement is used in multiple units, locomotives, passenger coaches, and freight wagons. The bearing set analyzed consists of cylindrical roller bearings NJ+NJP (WJ+WJP), with dimensions 130 × 240 × 80 mm. The remaining key bearing parameters are presented in Table 1.

The computational model was developed to accurately reflect the real installation and operating conditions of axlebox bearings. In particular, it accounted for axle journal deflection, the stiffness of the axlebox mounting, and the loads acting on the wheelset. Figures 1 and 2 show the general 3D model and its geometric details. The positive Y-axis corresponds to the direction of the vertical load transmitted from the bogie frame and vehicle body. Axial loads act along the Z-axis and reverse direction depending on the load case. When the axial load acts in the +Z direction, it is transmitted through the guide rib raceways of the outer bearing in the left axlebox (NJP1) and the inner bearing in the right axlebox (NJ2). When the axial load reverses, the load is carried by NJP2 and NJ1 respectively.

The axlebox housing was modelled as a cylindrical structure fixed with connection type “Rigid connection” with predefined stiffness values. The tilt stiffnesses were selected to reflect the characteristics of symmetrical axlebox mounting. The inner and outer rings of the bearing were constrained using “Fixed” connections, meaning that the operating radial clearance was not an outcome of the model, but instead specified directly as an input parameter. This approach ensured full control over clearance values without modifying fits or interference conditions.

The lubricant used in the analysis was Mobilith SHC 100, which is widely applied in railway

Table 1. Parameters of NJ and NJP bearings

Parameter	Value
Inner diameter	130 mm
Outer diameter	240 mm
Bearing width	80 mm
Number of rollers	17
Bearing pitch diameter	184 mm
Roller diameter	27 mm
Roller length	48 mm
Basic static load rating according to ISO 76	792690 N
Basic dynamic load rating according to ISO 281	548800 N
Roller profile modification	logarithmic (design stress: 2150 MPa)
Inner ring / outer ring raceway modification	none

axlebox bearings. The operating temperature of the bearings was set to 80 °C. This temperature affected the properties of the lubricant film, but did not influence the value of the operating radial internal clearance, which was defined as an input parameter of the model. The axial clearance of the bearing pair in each axlebox was defined as 0.65 mm and remained constant for all calculation cases. The rotational speed of the wheelset axle was set to n = 1140 rpm, which, for a wheel diameter of 820 mm typical of regional passenger rolling stock, corresponds to a vehicle speed of Vmax = 176 km/h.

Table 2 presents the bearing housing stiffness parameters as defined in the model. The tilt stiffness of the bearing arrangement about the X and Y axes is consistent with the expected stiffness of the swing-arm wheelset guidance systems used in regional passenger vehicles.

The points marked as Lw1 and Lw2 in Figure 2 correspond to the wheel location on the axle. The radial load F_r (108 kN) and the axial load F_a (16.42 kN) were applied at these points. The details are provided in Table 3.

Under normal operating conditions of railway wheelsets, the axial load cyclically reverses direction. For this reason, each calculation case consists of two phases: in the first phase, the axial load acts in the +Z direction for 50% of the simulation time (Load case: 1+Fa), and in the second phase, it acts in the opposite direction (–Z) for the remaining 50% (Load case: 2-Fa). The details regarding the direction and duration of the axial load are presented in Table 4.

The analyses were carried out using a modified logarithmic roller profile correction with a Design Stress parameter of 2150 MPa, which corresponds to a profile drop of 15 µm.

RESULTS AND DISCUSSION

Calculations were performed for 17 different load cases (CC_1 to CC_17). Table 5 presents the results of the modified reference rating life (L2mr) of the bearings according to ISO/TS 16281 for a reliability level of 98% (life modification factor for reliability according to ISO 281: $\alpha_1 = 0.3659$). The table also includes the maximum contact pressure values on the primary raceways of the bearings (p_{max}), as well as the percentage of fatigue life consumed during the simulation time of 11,500 hours (Damage %), which corresponds to a vehicle mileage of 2 million kilometers for the analyzed case. The results are presented separately for the outer bearings (NJP) and the inner bearings (NJ).

For calculation case CC_11, which corresponds to the configuration in which both bearing rows operate with identical radial internal clearance of 50 µm, the difference in calculated bearing life between the outer and inner rows exceeds 17,000 hours, with the NJP bearings achieving noticeably greater durability. The NJP bearings show better results in every calculation case in which their operating radial internal clearance is higher than the clearance of the adjacent bearing row. They also exhibit greater results in cases CC_10 and CC_12, even though their clearance is 10 µm lower than that of the NJ bearings.

In contrast, the NJ bearings achieve better results in cases CC_2, CC_4, CC_6, CC_8, CC_14 and CC_16, that is, in all configurations where the radial internal clearance of the inner row (NJ) exceeds that of the outer row by at least 20 µm. The percentage of fatigue life consumed is most balanced between the two rows in calculation cases CC_8 and CC_14, where the clearance

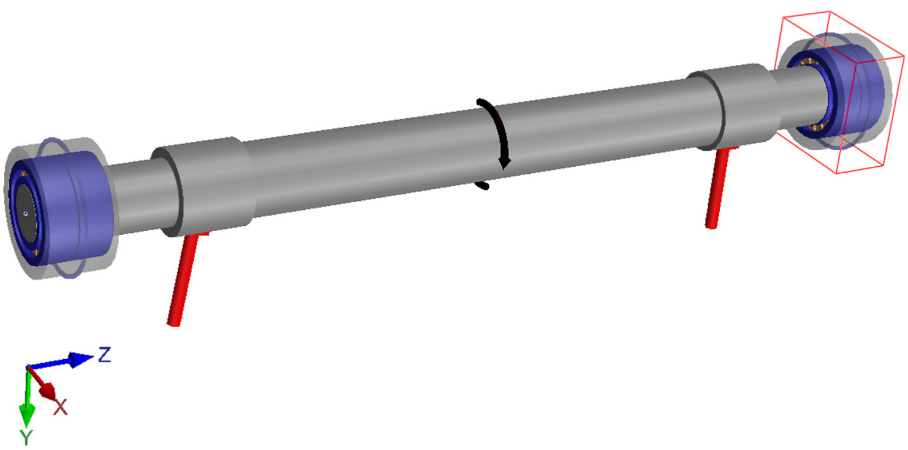

Figure 1. 3D view of the computational model (source ROMAX)

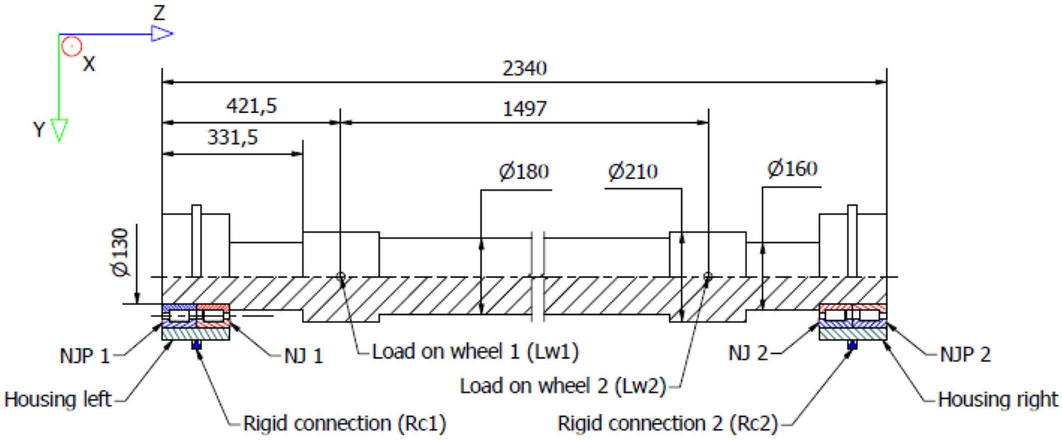

Figure 2. Details of the computational model geometry

Table 2. Parameters of housing ground. Rigid connection Rc1, Rc2

Bearing housing stiffness	Value
Axial stiffness	1e9 N/mm
X radial stiffness	1e9 N/mm
Y radial stiffness	1e9 N/mm
Torsional stiffness	1e12 Nmm/rad
X tilt stiffness	6,86e7 Nmm/rad
Y tilt stiffness	6,86e7 Nmm/rad

difference is 20 µm and the row with the larger clearance is located on the wheel side. A difference in calculated damage of less than 20% between the rows is also observed for the configurations analyzed in cases CC_4, CC_6, CC_10, CC_12 and CC_16.

In bearing assemblies composed of multiple rows, it is common practice to calculate the life of the entire system, rather than evaluating the life of each bearing row individually. This approach is particularly important for designs in which operational reliability and the ability to maintain safe operation depend on both rows sharing the load simultaneously, and where the failure of a single row is regarded as a failure of the complete system.

In the case of an axlebox arrangement that uses two single-row cylindrical roller bearings installed as a complementary pair, the failure of one bearing row must unquestionably be considered equivalent to the failure of the whole system. This is because the remaining row, although still functional, would be subjected to increased loading, while the pairing conditions would deteriorate and the operating temperature of the entire assembly would rise. As a result, the second bearing row would experience premature and uncontrolled damage.

The system life for a configuration consisting of two single-row bearings is calculated using Equation 1 [8, 14].

$$L_{sys} = (L_{row1}^{-9/8} + L_{row2}^{-9/8})^{-8/9} \quad (1)$$

Table 4. Axial load for single calculation case

Name	Direction	Duration (hrs)	Force [kN]
1+Fa	+Z	5750	16.42
2-Fa	-Z	5750	-16.42

Table 3. Loads applied at designated load points

Load point	Direction	Load case: 1+Fa	Load case: 2-Fa
		Force [kN]	Force [kN]
Lw1 (left wheel)	X	0	0
	Y	-108	-108
	Z	16.42	0
Lw2 (right wheel)	X	0	0
	Y	-108	-108
	Z	0	-16.42

Table 5. The results of the modified reference rating life of the bearings

Calculation Case (CC)	Variation of radial clearances NJP/NJ [μm]	NJP p_{max} [Mpa]	NJ p_{max} [Mpa]	NJP Damage (%)	NJ Damage (%)	NJP L2mr acc. ISO/TS 16281 [h]	NJ L2mr acc. ISO/TS 16281 [h]
CC_1	50/0	1184	1278	13.1	65.4	87475	17581
CC_2	0/50	1241	1205	41.7	21	27549	54860
CC_3	50/10	1193	1292	13.8	64.4	83312	17851
CC_4	10/50	1254	1213	40.6	22.3	28298	51604
CC_5	50/20	1208	1304	15.6	62.8	73882	18307
CC_6	20/50	1264	1237	38.3	26.2	30049	43887
CC_7	50/30	1226	1312	18.5	60	62324	19165
CC_8	30/50	1269	1267	34.8	32.9	33028	34917
CC_9	50/40	1245	1313	22.6	55.3	50934	20796
CC_10	40/50	1269	1289	31.6	40.6	36445	28335
CC_11	50/50	1266	1311	28.1	49.8	40957	23106
CC_12	50/60	1288	1305	34.9	44.2	32975	25997
CC_13	60/50	1261	1332	24.9	60.6	46159	18988
CC_14	50/70	1311	1301	43.2	39.7	26625	28960
CC_15	70/50	1259	1352	22.5	72.8	51033	15788
CC_16	50/80	1333	1299	53.1	36.1	21671	31816
CC_17	80/50	1263	1370	21.6	84.9	53222	13542

where: L_{row1} – calculated life of row 1, L_{row2} – calculated life of row 2.

Figure 3 presents a summary of the calculated life of the system composed of the NJ+NJP bearing arrangement. For the configurations with operating radial clearances of 50/20 and 20/50 μm, the difference in the calculated modified life of the entire system is nearly 20%.

Figures 4 and 5 present the plots showing the contact stress distribution in the contact zone between the rolling elements and the inner ring raceway of the bearings in the left axlebox, for selected calculation cases with opposite arrangement of radial internal clearance and for load case LC 1 + F_a. Due to the asymmetric distribution of radial internal clearance, the magnitude of the maximum contact stresses changes, as does the circumferential load distribution within each bearing row and the pressure distribution along the rolling elements. Figure 6 presents the corresponding stress maps for the bearing system with a symmetrical arrangement of operating radial clearance (50/50 μm).

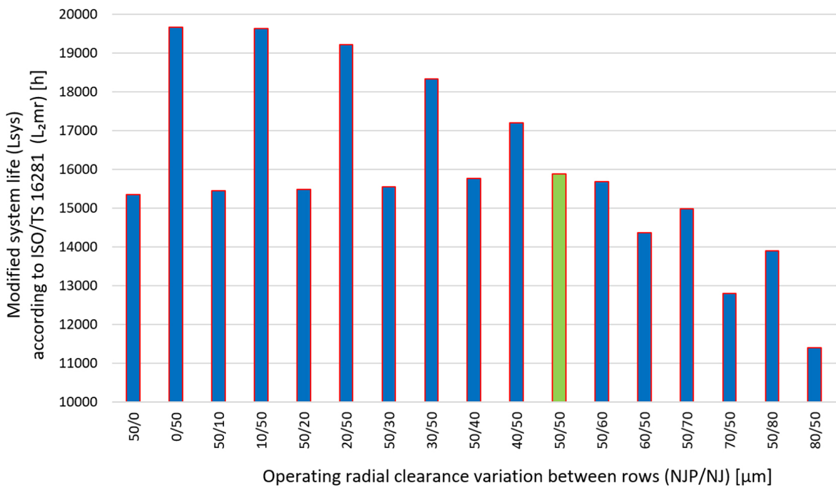

Figure 3. Modified system life for all calculation cases.

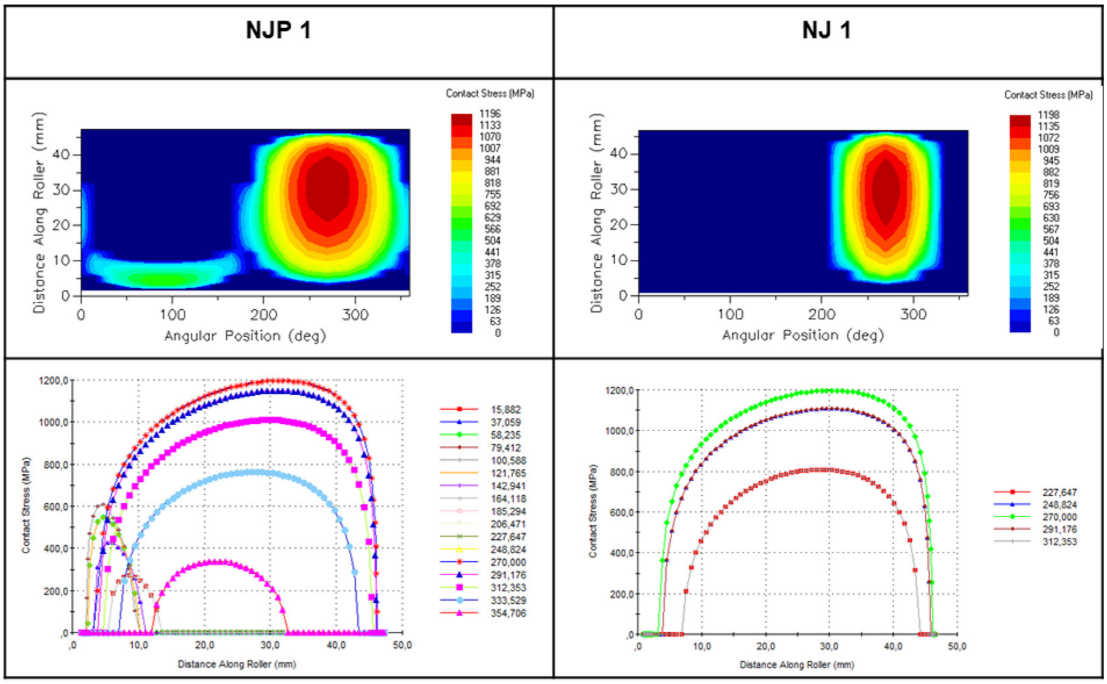

Figure 4. Inner raceway contact stress for CC_2, LC 1+Fa

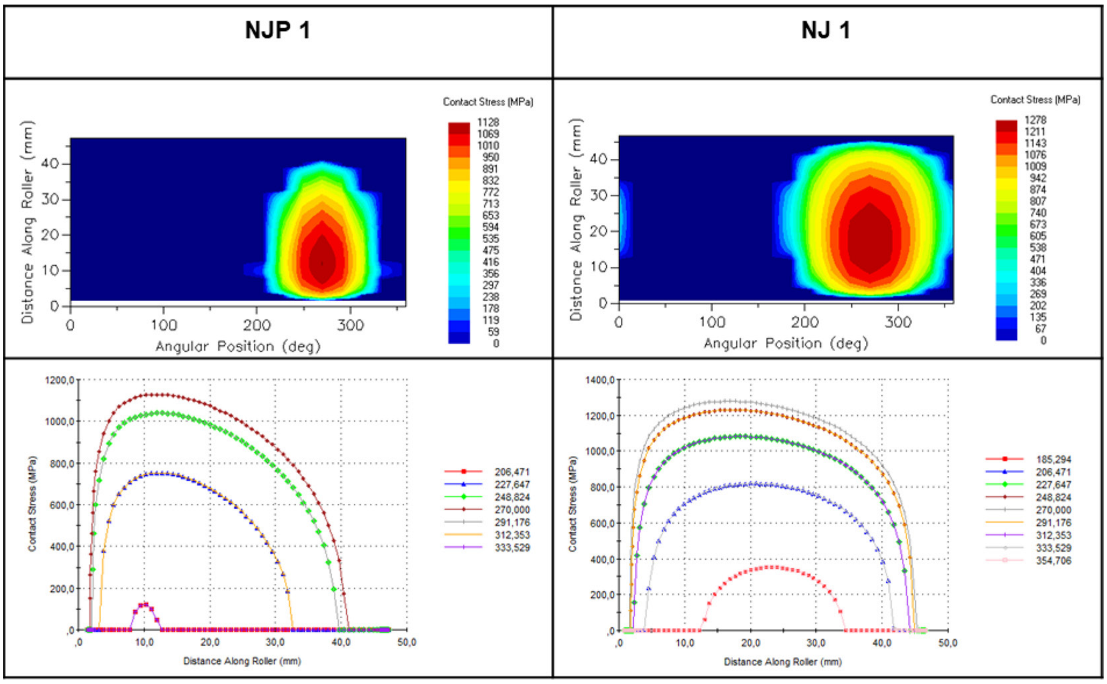

Figure 5. Inner raceway contact stress for CC_1, LC 1+Fa

As the asymmetry of the radial internal clearance increases, the maximum contact stresses shift toward the area located closer to the end face of the rolling elements. This behavior is associated with the increasing misalignment of the outer rings relative to the inner rings and is a natural consequence of the uneven radial clearances within the pair of cylindrical roller bearings. Table 6 presents the results of the analysis concerning the influence of radial internal clearance on the misalignment between the bearing rings. For the symmetrical clearance configuration, the misalignment did not exceed 0.12 mrad, whereas for a clearance difference of 50 µm, the maximum value did not exceed 0.35 mrad, which remains acceptable for cylindrical roller bearings [7].

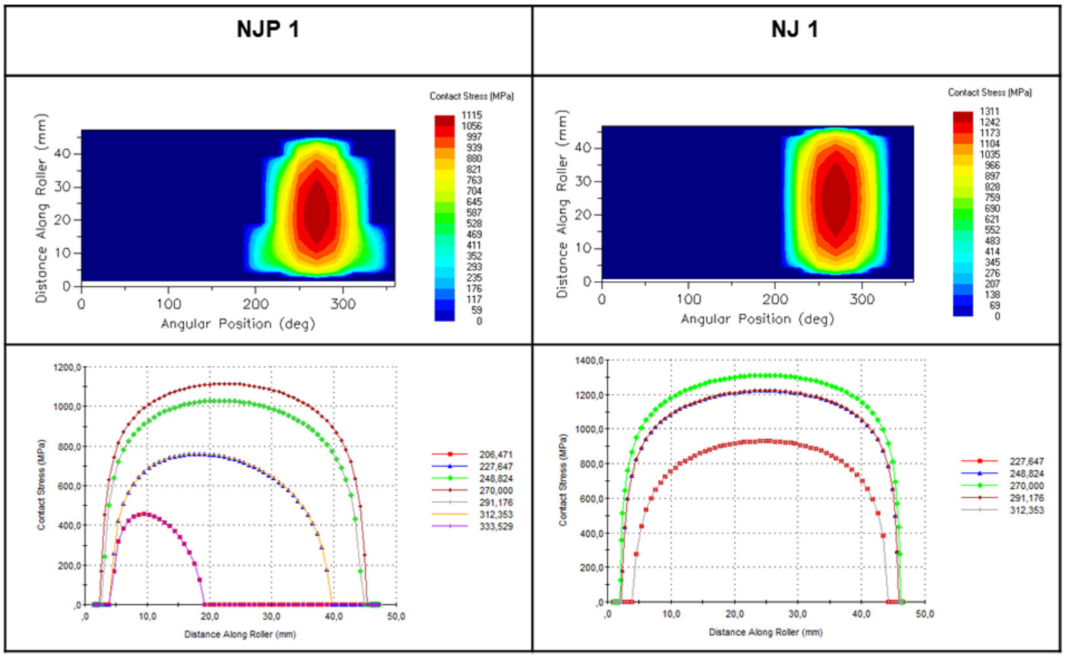

Figure 6. Inner raceway contact stress for CC_11, LC 1+Fa

Table 6. Misalignments IR w/r OR for calculation cases CC_1, CC_2, CC_11 and LC 1+Fa

Variation of radial clearances NJP/NJ [µm]	Relative misalignments (inner ring w/r to outer ring) [mrad]			
	NJP 1	NJ 1	NJ 2	NJP2
0/50	0.2775	0.2280	0.1583	0.2300
50/0	0.1978	0.2669	0.3433	0.2902
50/50	0.0945	0.0292	0.1193	0.0540

CONCLUSIONS

The analyses carried out in this study demonstrate that the differences in radial internal clearance (RIC) between the rows of cylindrical roller bearings installed within the same axlebox have a significant influence on load distribution, contact stress levels, and the overall life of the bearing system. On the basis of the obtained results, the following conclusions can be drawn:

Unequal radial internal clearance values leads to an asymmetric load distribution. When the operating radial internal clearance differs between the bearing rows, the row with the smaller clearance becomes stiffer and carries a greater share of the load over a smaller contact area. This results in higher local contact stresses and may lead to accelerated fatigue wear of that row.

Even small differences in operating RIC (in the range of 20–30 µm) may, depending on the configuration, lead to either a reduction or an increase in bearing life. From a system life perspective, the symmetrical distribution of radial internal clearance between the rows of the axlebox bearings is not the optimal configuration.

Selecting an appropriate configuration of operating RIC values differences can lead to a several-tens-percent increase in axlebox bearing life. The most balanced utilization of fatigue life between the NJ and NJP rows was obtained for configurations in which the difference in radial internal clearance did not exceed 30 µm, and the row located on the wheel side (NJ) had the larger clearance. For such configurations, the differences in calculated damage levels did not exceed 20%. For the analyzed wheelset design and the load conditions typical of regional multiple units and passenger coaches, the most favorable configuration is one in which the operating radial clearance of the outer bearing row is 20 µm smaller than the radial clearance of the inner row.

Uneven radial internal clearance between the rows of a cylindrical roller bearing pair may affects the level of misalignment between the inner and outer rings. As the difference in radial internal clearance between the rows increases, the degree of misalignment also increases. For a clearance difference of 50 µm, the misalignment did not exceed 0.35 mrad, which is an acceptable value for cylindrical roller bearings.

When, for practical and economic reasons, it is not possible to install single-row cylindrical roller bearings such that the row with the smaller radial internal clearance within a given axlebox is always located on the outer side, it is recommended to use bearings with a smaller manufacturing clearance spread or bearings factory-matched by the manufacturer.

The results of the analyses have practical applicability, and the implementation of the conclusions drawn in this study may contribute to improving the safety of railway operations.

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