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THE MODIFICATION OF THE RACEWAY PROFILE IN THE DOUBLE ROW SLEWING BEARING

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Abstract

The slewing bearings are applied in heavy working machines and operated in extreme conditions.

A characteristic feature of these bearings are a high load which determining a large deflection of a contact zone rolling element - raceway. This phenomenon combined with the effects of a bearing clearance causes a significant increase in a contact angle of the bearing. This in turn causes displacement of the contact zone to an undesirable position. In the construction of slewing bearing is applied of a large value of the osculation ratio. This leads to occur of large sizes of the contact zone identified in a radial cross-section. The sizes are comparable to values of the radius of the ball. The contact zone is type of quasi-linear. Effects of changes the position of the contact zone in the double-row ball slewing bearing has been presented in the paper. The raceway profile for such bearing consists of the arc section changing in the radial section. When the contact zone includes a change point of curvature of the raceway profile it comes to a concentration of a contact stress, and this is unfavourable for operation of the bearing. In order to eliminate this phenomenon to the profile introduced a transition curve. For this purpose was selected a clothoid. The curve ensures a gradual change of curvature from the arc section of the profile to the zero curvature of the straight profile section. The raceway profile becomes the smooth curve of the second rank. In the article are presented a numerical model of the contact zone for the double-row ball slewing bearing and the distributions of a pressure in the contact zone for the ordinary and modified raceway profiles. The calculation results have been presented as graphs of the distributions of the pressure along the contact zone. It has been shown that the introduction modification of the raceway profile eliminates the concentration of the pressure along the contact zone profile. The results obtained can be used during design of the raceway profiles of the double-row ball slewing bearing.

Keywords: *slewing bearings, contact zone, fem analysis*

1. Introduction

The slewing bearings are applied especially to working machines such as excavators, cranes, wind turbines and others, and they are subjected to extremely high loads. The result of high loads is extreme working conditions of a contact zone rolling element - bearing raceway. The large load of the contact zone causes a change it is the geometry. In ball slewing bearings, which are the subject of this study, the contact angle is subject to the significant changes. Nominal contact angle for a typical two-row ball slewing bearing is 45°. The parameters of the raceway profile in the slewing bearing are shown in Fig 1. The raceway profile consists of arc section and a straight section, which are tangential, each other, therefore the raceway profile are smooth curve of class C^1.

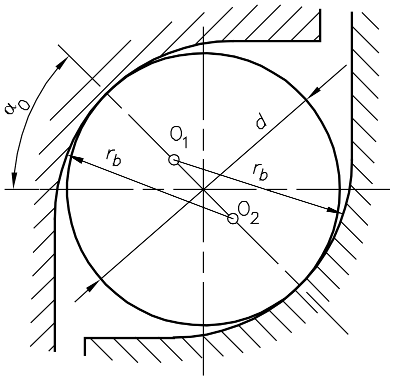

Fig. 1. The race profile of two-row slewing bearing

The real value of the contact angle for a ball slewing bearing may be significantly different from the nominal value. This issue is widely discussed in [4]. The changes of a value of the contact angle are caused by two factors: deflection of the contact zone and bearing clearance. A change of the contact angle are also dependent on a value of an osculation rate k_p, i.e. the quotient of the ball radius and a radius of the raceways profile. For slewing bearings apply a large value of the osculation rate $k_p = 0.97$ and even 0.98. It makes that the contact angle for the maximum load is increased by several degrees [4]. Small value of axial clearance exists in slewing bearings as the result of technological reasons. During operation the bearing, the bearing clearance is increased, usually due to a wear raceway. Bearing manufacturers give a limits value of the bearing clearance, which it is, described an indicator of axial clearance as the ratio of a value of the clearance and the ball diameter. For a limit values of bearing clearance which are recommended by Rothe Erde [9] a value of a contact angle of the contact zone is increasing by more than 35° (at the value $k_s = 0.025$, $k_p = 0.97$) [4]. This means that the initial angle of the contact zone for an unloaded bearing much different from the nominal contact angle of the bearing. The nominal value of the contact angle has importance only at design. In rolling bearings the balls are in contact with a concave radius of raceway, hence by operate an extreme load in the contact zone; the semimajor axis of contact ellipse reaches a significant value, comparable to the size of balls. Parameters of the contact zone for the ball slewing bearings loaded are presented schematically in Fig. 2.

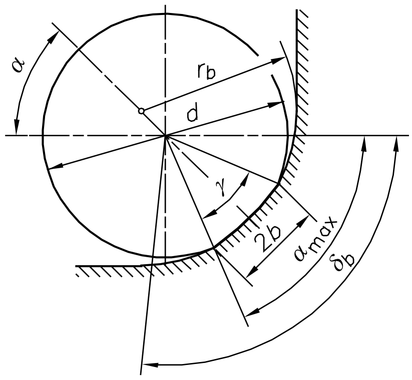

Fig. 2. Schema of contact zone of two-row ball slewing bearing under load: γ – angle of contact area, α_{max} – angle of scope of contact zone, δ_b – angle of race profile

For a standard shape of the raceway profile, the correct functioning of the bearing requires that:

$$\alpha_{\max} \leq \delta_b \,. \tag{1}$$

At high values of the osculation rate (slight differences between the radius of raceway profile and radius of ball); the angle δ_b is slightly larger than 90°. All factors of the above mentioned when are simultaneously activated cause that the contact area moves and may transgress beyond a basis the arc section of raceway profile and may include the straight section of raceway profile. In this case, on contact surface a sudden change of a curvature profile occurs due to a smoothness of the curve of the class C^1. In work [5] it is demonstrated that sudden change curvature of a body profile which are in a contact causes a concentration of pressure on the contact surface and such a phenomenon occurs even at relatively small curvature of arc section the raceway profile. In relation to double-row ball-slewing bearing, the results of an analysis of this phenomenon by using numerical model (FEM) of the contact zone have been discussed in [6]. Graph of a distribution of the pressure in the radial cross-section of the contact zone are presented in Fig. 3. Distribution of the pressure is similar for each the value of forces and has characteristic a quasi-linear zone located in an area of half a length of the contact zone. A distinct increase of the pressures shown in the Fig. 3 is located near the change point of curvature from the arc section to the straight section.

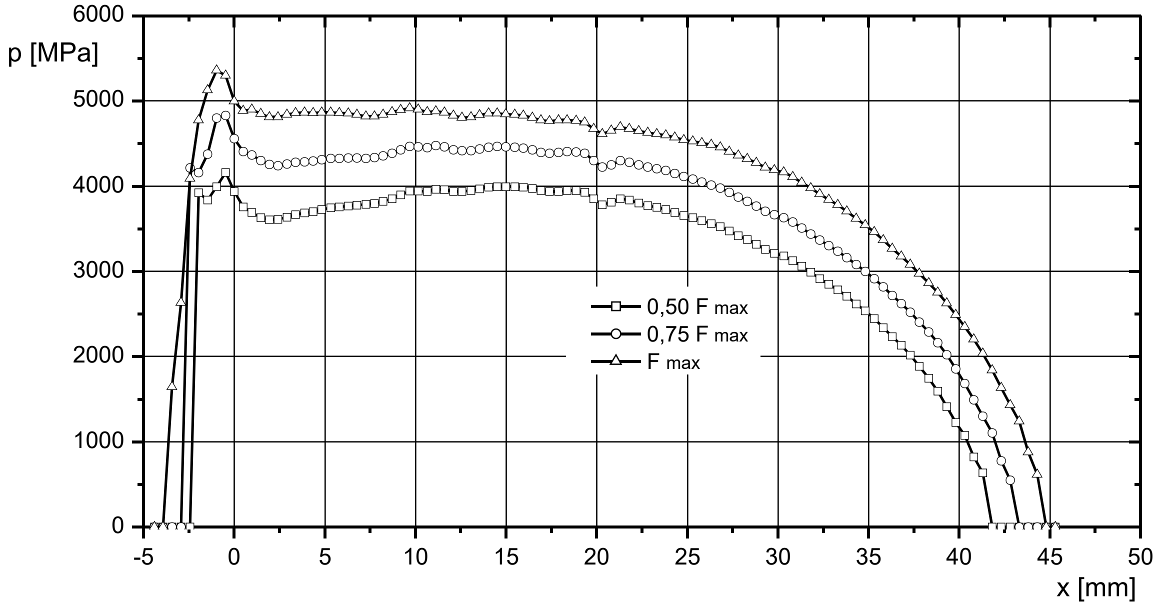

Fig. 3. Distribution of pressure on contact zone of two-row ball slewing bearing for $k_p = 0.98$, $d = 76.2$ mm, $F_{max} = 448$ kN, according to [6]

2. A transition curve

In order to avoid undesirable increase of the pressure the profile curves of bodied in the contact zone require a smoothness of type C^2, that means that individual sections of the profile should have the same curvature at point of tangency. This solution requires introduce the profile of a transition curve. The profile has been divided into three sections: an arc section (original) – marked as O1, a transition curve section O2, a straight section O3. The transition curve has been assumed a clothoid, which the variable curvature allows join two curves of arbitrary curvatures.

A general equation of a clothoid is described the dependency:

$$L = a^2 \cdot K , \tag{2}$$

where:
L – the arc length of the curve,
K – curvature,
a^2 – factor of proportionality, which is a constant for a specific clothoid.

The curvature of the clothoid is increased from zero (when $L = 0$), to a value of any. Therefore, it can join of a line segment about zero curvature with a segment of a circular arc with a radius R that is a reversal of the curvature. Individual parameters of clothoid are related dependencies:

$$a^2 = L \cdot R = 2\tau \cdot R^2 = \frac{L^2}{2\tau}, \tag{3}$$

where:
R – radius of curve,
τ – angle of sense a tangent.

Coordinates of clothoid in a Cartesian coordinate system can be determined by using the sine and cosine of Fresnel:

$$X = \int_0^L \cos \frac{L^2}{2a^2} dL, \tag{4}$$

$$Y = \int_0^L \sin \frac{L^2}{2a^2} dL, \tag{5}$$

which after performed the integration and expansion in series of the function integrand are obtained the formulas for calculating a coordinates of the transition curve:

$$X = L - \frac{L^5}{40a^4} + \frac{L^9}{3456a^8} - \cdots, \tag{6}$$

$$Y = \frac{L^3}{6a^2} - \frac{L^7}{336a^6} + \frac{L^{11}}{42240a^{10}} \cdots. \tag{8}$$

In order to fulfil an application of clothoid it should calculate the new coordinates of a centre of the arc section X_s, Y_s and displacement of the straight section H:

$$X_s = X - R\sin\tau, \quad Y_s = Y + R\cos\tau, \tag{9}$$

$$H = Y - R(1 - \cos\tau). \tag{10}$$

A scheme of a modification of the profile is shown in Fig. 4.

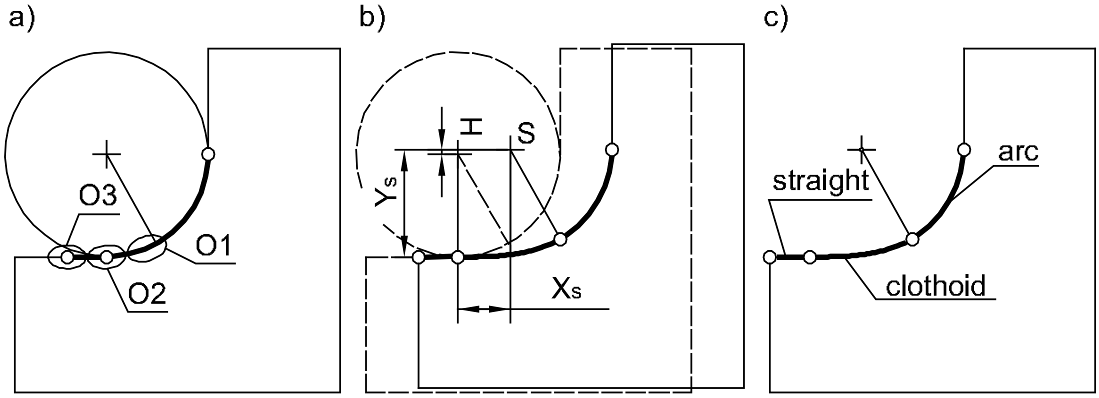

Fig. 4. The designation of the modified profile raceway (a), parameters of the modified profile (b), raceway profile after modification (c)

3. Numerical models of contact zone

The analysis of the contact zone was conducted by using the numerical models and ADINA programs [1]. To computations utilized the sizes of slewing bearing 2.2P.Z.N.76.2500.0.0.00.C [7] which the scheme and mainly dimensions are shown in Fig. 5. A diameter of the rolling elements for the object being under consideration is d = 76.2 mm and the nominal contact angle has value α_n = 45°.

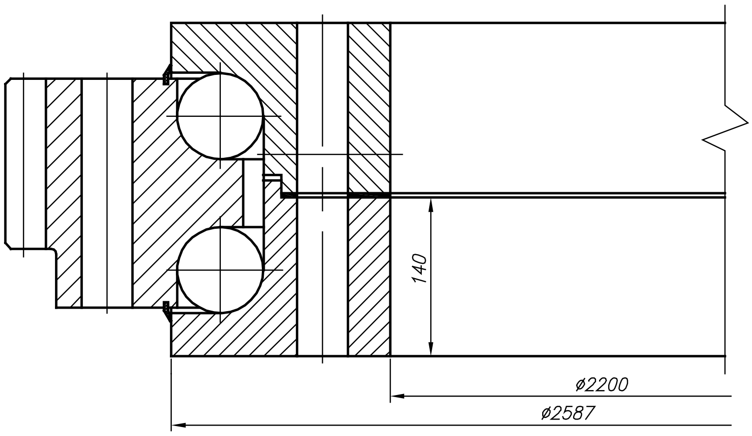

Fig. 5. Two-row ball slewing bearing 2.2P.Z.N.76.2500.0.0.00.C (according to [7])

For the purposes of analyse it was assumed the contact angle $\alpha = 60°$. This value corresponds approximately to a value of the initial contact angle for the slewing bearing with a small axial clearance with the indicator of axial clearance $k_s = 0.1$.

Geometric simplifications of the numerical model are following: area of balls was limited to 1/4 of its volume, section of the raceway corresponds to a half of pitch circumferential of the bearings, due to a large track diameter of the slewing bearing and the small size of the raceway the circumferential curvature of raceway was omitted. On the surface the balls and the raceways the sectors of a contact was separated, and their size included of the all area of the contact zone of these elements. The contact zone was divided into segments in size 0.5 mm that corresponds to 0.658% of the rolling element (ball). In the model were used 8-node finite element of type 3-D SOLID. A mesh of the model is shown in Fig. 6.

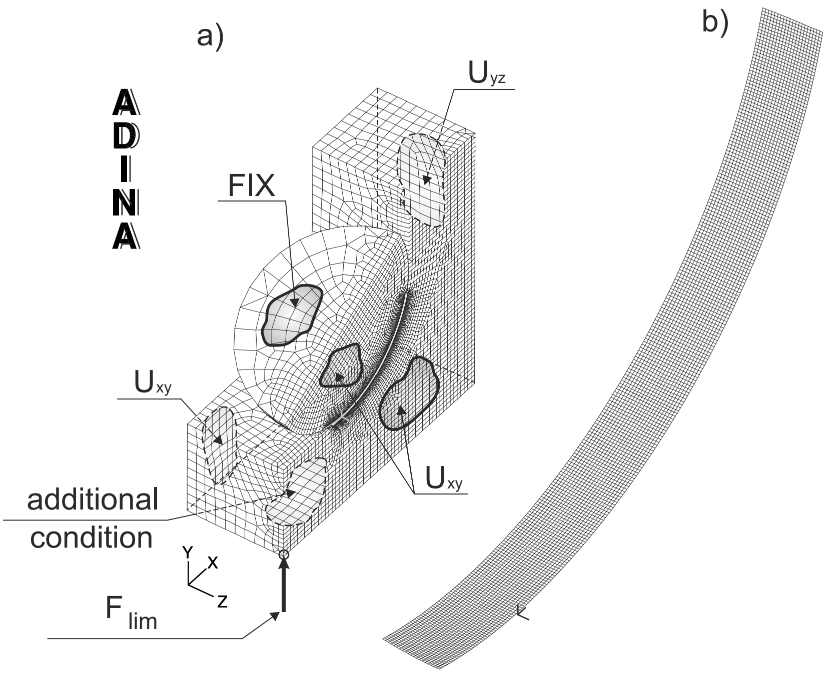

Fig. 6. The mesh of numerical model of contact zone (a) with contact surface (b) – additional condition = identical displacement on Y-axis

Similarly like in work [4] it was assumed the bilinear elastic-plastic the material model (Fig. 7).

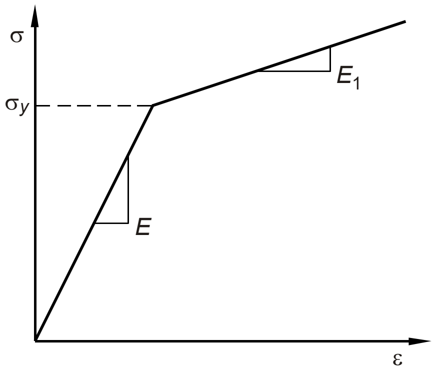

Fig. 7. Bilinear model of an elastic-plastic material, $E_1 = 0.1\ E$

A load of the contact zone is a function of the sizes of the rolling elements, osculation rate and hardness of raceway. A load limit of the contact zone is assumed according Palmgren's criterion [8] and it defined by a relative plastic deformation of the contact zone:

$$\frac{\delta_{pl\lim}}{d} = 2 \cdot 10^{-4} . \tag{11}$$

On the basis of an empirical Eschmann's formulas [2], it can determine the equation, which is used to calculating the limited load of the contact zone [3]:

$$F_{\lim} = 9.9626 \cdot 10^{7} \frac{f_H\, d^2}{c_p^2} , \tag{12}$$

where: f_H – hardness factor:

$$f_H = \left(\frac{HV}{750} \right)^2 , \tag{13}$$

$$c_p = \frac{1.5}{\pi\, \mu_H\, \nu_H} \left[\frac{E}{3(1-\nu^2)}\, d\, \Sigma\rho \right]^{\frac{2}{3}} , \tag{14}$$

$\Sigma\rho$ – sum of curvatures of contact bodies, μ_H, ν_H – Hertz's factors.

The calculations were performed on the models with the four values of the length of the transition curve (clothoid) which the parameters are contained in the Tab 1.

Tab. 1. Parameters of transition curve in raceway profile of two-row ball slewing bearing

Length of clothoid L_c [mm]	5	10	20	40
Tangential angle [rad]	0.06447	0.12895	0.25789	0.51579
Proportion factor [–]	193.8775	387.7551	775.51020	1551.0204
Radius of curvature R_c [mm]	38.77551			

The sample distributions of the pressure in the contact zone, which have been obtained by performed of calculations, are shown in Fig. 8. Influence of the length of clothoid on the size of the contact area and the maximum pressures is clearly visible. In the case of the clothoid length L_c = 40 mm the length of the contact area is shortened by about 20% and it results an increase of the pressure considerably above values of the pressure identified for the profile unadjusted. The quasi-linear distribution of the pressure is disturbed. This effect occurs to a lesser extent at L_c = 10 mm and L_c = 5 mm. Changing of the length of a contact field are marginal and decreases the maximum pressure values. In the Tab. 2 are contained value of the maximum contact stress

p_{O2}, which appeared in section O2 and their percentage change Δp related to the pressure values obtained on the basis of the analysis of profile unadjusted.

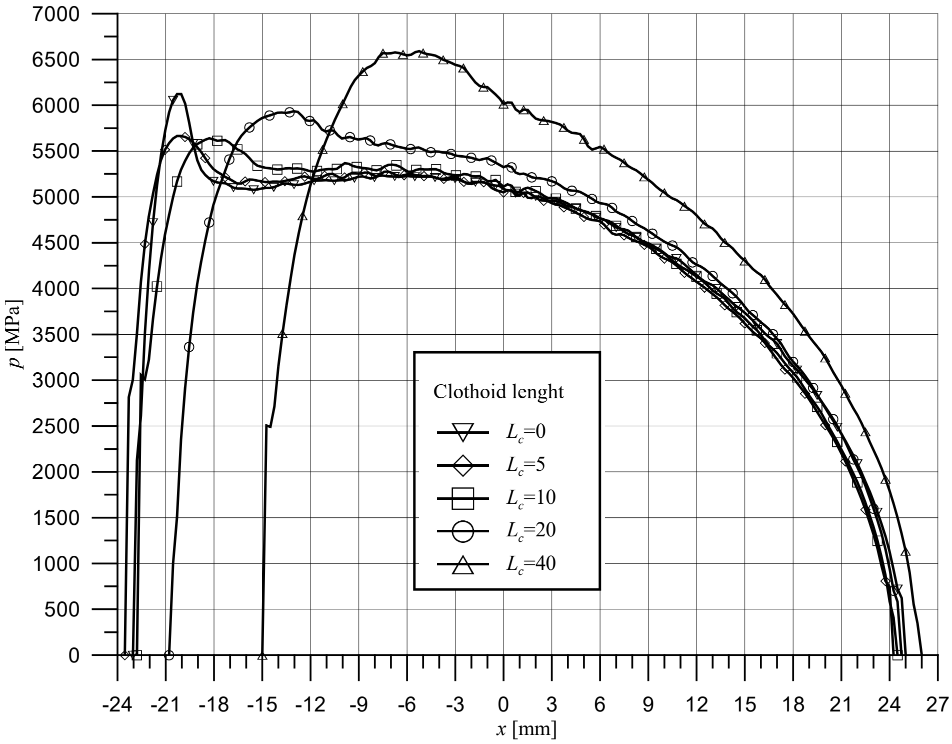

Fig. 8. Pressure distribution on modified profiles for different length of clothoid (for 750 HV)

Tab. 2. Comparison of results of profile traces modification

Hardness of trace	$L_c = 0$	$L_c = 5$ mm		$L_c = 10$ mm		$L_c = 20$ mm	
	p_{O2} [MPa]	p_{O2} [MPa]	Δp [%]	p_{O2} [MPa]	Δp [%]	p_{O2} [MPa]	Δp [%]
54 HRC	4469.71	4151.91	– 7.11	4260.32	– 4.68	4645.85	3.94
56 HRC	4832.43	4473.33	– 7.43	4552.44	– 5.79	4920.06	1.81
58 HRC	5222.06	4824.76	– 7.61	4871.83	– 6.71	5220.07	– 0.04
60 HRC	5636.74	5205.97	– 7.64	5213.70	– 7.51	5546.36	– 1.60

4. Final remarks

Carried out in the article analysis allows to formulate the following comments.

1. In the double-row ball, slewing bearings under the large load and at medium values of axial clearance the contact angle is significant increasing and it results a disadvantageous displacement of the contact zone. In the place of changing, a curvature of the profile is a concentration of the pressure, which is disadvantageous due to a contact fatigue.
2. A modification of the raceway profile was performed by introducing the transition curve – clothoid. This ensures the smooth class of the generating line of profile C^2.
3. Numerical calculations have performed by use the FEM models proves the validity of the assumed solution. Analysis of the distribution of the pressure along the contact area can conclude that the best results are obtained when the length of the clothoid is in range about 10% of a ball diameter of the bearing. Then obtained the reduction of pressures above 7% of the maximum value at a small change of the sizes of the contact area and maintaining the characteristic distribution of the pressure.

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