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ANALYSIS OF THE INFLUENCE OF INTERNAL RADIAL CLEARANCE ON THE LOAD DISTRIBUTION OF THE ROLLING BALL BEARING

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RESEARCH ARTICLE

ABSTRACT: The distribution of the external radial load on rolling bodies of bearing is uneven. This is a statically undefined problem, so for the analysis of load distribution beside equilibrium conditions need to be introduced and supplemental one which are based on the relationship between the contact deformation of the contact parts and loads. The unevenness of the distribution is greater considering the influence of the inner radial clearance. Purpose of the paper is to determine the load transmitted by the most heavily loaded rolling body as well as the other rolling bodies, used analytical and numerical approach.

KEY WORDS: radial ball bearing, internal radial clearance, load distribution, Finite Element Method

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ANALIZA UTICAJA UNUTRAŠNJEG RADIJALNOG ZAZORA NA RASPODELU OPTEREĆENJA KOD RADIJALNOG KUGLIČNOG LEŽAJA

REZIME: Raspodela spoljašnjeg radijalnog opterećenja na kotrljajna tela ležaja je neravnomerna. To je statički nedefinisan problem, pa je za analizu raspodele opterećenja pored ravnotežnih uslova potrebno uvesti i dopunske koje se temelje na odnosu između kontaktne deformacije kontaktnih delova i opterećenja. Nejednakost raspodjele je veća s obzirom na uticaj unutrašnjeg radijalnog zazora. Cilj rada je da se odredi opterećenje koje prenosi najteže opterećeno telo valjaka kao i druga tela valjanja, koristeći analitički i numerički pristup.

KLJUČNE REČI: radijalni kuglični ležaj, unutrašnji radijalni zazor, raspodela opterećenja, metoda konačnih elemenata

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1. INTRODUCTION

The distribution of the external radial load to the roller bodies of the radial ball bearing is uneven which means that at the same time all balls are not equal in the transfer of loads from one ring to the other. The total external load is transmitted from one ring to the other only through a certain number of total balls. The unevenness of the distribution of the external load is influenced by the intensity of the load, the inner radial clearance, the elastic deformation of the bearing rings, the internal bearing geometry and other factors. In this paper, a detailed analysis of the influence of the inner radial bearing clearance on the distribution of the external load on the roller bearing bodies is given.

2. DETERMINATION OF EXTERNAL LOAD DISTRIBUTION TO THE BALL BEARING ROLLING ELEMENTS

It is a statically undefined problem, therefore, for static equilibrium analysis it is necessary to introduce additional ones which are based on the connection between the contact deformations of the connected parts of bearing (moving one ring in relation to the other under the influence of the external load) and the load.

Consideration of the load distribution on the ball bearing rolling elements is carried out assuming that the bearing parts are stationary; that all balls of the exact dimensions and shapes and that the diameters and radii of the rolling path of the rings are of perfectly accurate measures, shape and position.

2. 1 Radial ball bearing with internal radial clearance

An analysis of the distribution of the external load to the ball bearing rolling elements will take into account that the housing in which the outer bearing ring is fitted is hard (does not change the shape due to the load) and that the direction of the external load action passes through the center of one of the ball and is directed to the ball. The external radial force F_r is distributed unevenly to a number of balls z_s in a loaded zone below the meridian plane which represents the plane of the bearing normal to the direction of the attack line of force (Figure 1). The Meridian plane divides the bearing into two zones - one is placed unloaded and in the other there are loaded balls. Balls whose centers lie at the meridian level do not transmit the load.

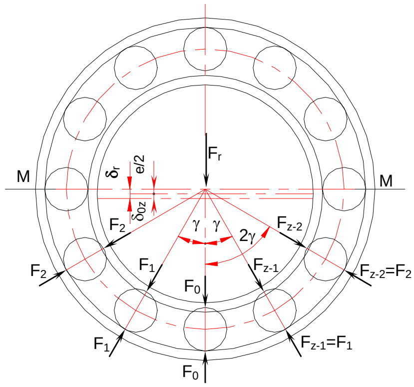

Figure 1. Load distribution to ball bearing rolling elements of radial bearings with internal radial clearance

From the static equilibrium conditions, the relationship between the external radial load and the force at the place of the most loaded ball and the force at the place of other balls can be determined. As this is a statically indeterminate/undefined problem,additional conditions are introduced which connect elastic contact deformations and loads [1], [2], [3]. It is assumed that in the unloaded state at the centric position of the rings the touching of the balls and the outer ring is achieved and that there is a radial clearance which is equal to half of the total clearance between the balls and the inner ring, as shown in Figure 1.

The distribution of the external load on the ball bearing rolling elements of radial bearings with radial clearance is radically uneven compared to the bearing without radial clearance, as the clearance increases with the increase in the load area and increases the intensity of the force at the point of the most loaded ball. Therefore, the total contact deformation at the place of the most loaded ball δ_{0z} at the initial touch point is higher than the corresponding contact deformation of the bearing without a radial clearance δ_0.

The total contact deformation of the coupled parts at the initial point of contact at the place of the most loaded ball in the existence of the radial clearance δ_{0z} is determined by iterative method using the Newton's iteration method (tangent method) [2], where by determining an unknown parameter δ_x we obtain:

$$\delta_{0z} = \frac{e}{2} \cdot \delta_x \tag{1}$$

When δ_{0z} is determined, the total radial displacement of the bearing axis δ_r can be determined, and on the basis of this the total contact deformation at the position of the random i-th ball δ_{iz} can be determined. Depending on the calculated values of the total contact deformations δ_{0z} and δ_{iz}, the corresponding forces can also be determined at the place of the most loaded ball bearing with a radial clearance:

$$F_{0z} = C_\delta \cdot \delta_{0z}^{3/2} \tag{2}$$

and at the place of random i-th balls:

$$F_{iz} = C_\delta \cdot \delta_{iz}^{3/2} \tag{3}$$

By knowing the total contact deformation of the coupled parts at the place of the most loaded ball of bearing with a radial clearance, the factor of unevenness of load distribution on the balls of the given bearing can finally be determined:

$$k = \frac{F_{0z}}{\left(\frac{F_r}{z}\right)} = \frac{C_\delta \cdot \delta_{0z}^{3/2}}{\left(\frac{F_r}{z}\right)} \tag{4}$$

From the above expression, it can be seen that the factor of unevenness of load distribution on the balls of a given bearing depends on the size of the external radial load Fr, the number of balls z, the inner bearing geometry and the elastic modulus and the Poisson coefficients of the bearing parts (constant C_δ) and the total contact deformation of the coupled parts at the starting point of the contact δ_{0z}. For a particular bearing and at a given external load, the factor k is only in function of δ_{0z}. Since δ_{0z} depends on the external load and the internal radial clearance e, for the given external load factor k is the function of the inner radial clearance. As the higher values of the radial clearance increase the contact deformation of the coupled parts, the greater is the unbalanced load distribution factor of the balls of the given bearing k.

2.2 An analytical example of the determination of the external load distribution on the ball bearing rolling elements

Determination of external radial load distribution parameters on the ball bearing rolling elements is performed on a single ball bearing with radial contact 6206. This bearing has a wide application in industry. In the automotive industry, it is an inevitable part of the componentes in transmission system (gearboxes, differentials...), waterpump systems, alternators, wheels etc at commercial and special vehicles. The bearing characteristics required for calculation are given in the literature [3].

For different values of the radial clearance e whose value ranged from 0 to 20 μm and for different values of the external radial load whose values ranged from 1000 to 9000 N, there is obtained table of the results of the calculation (Table 1).

Table 1. Results of the calculation for ball bearing 6206

e	Results of the calculation		F_r, N				
μm			1000	3000	5000	7000	9000
0	F_0	N	487.2	1461.7	2436.2	3410.7	4385.2
	F_{1-8}		326.6	980.0	1633.4	2286.7	2940.1
	F_{2-7}		35.2	105.7	176.2	246.80	317.3
10	F_0	N	537.6	1543.8	2534.8	3522.2	4507.2
	F_{1-8}		301.7	950.3	1599.2	2249.3	2899.9
	F_{2-7}		-	5.7	43.0	90.8	143.3
20	F_0	N	581.8	1607.8	2618.1	3622.7	4620.1
	F_{1-8}		272.9	908.6	1554.6	2204.3	2853.4
	F_{2-7}		-	-	-	0.962	23.4

Based on the obtained results, the load distribution dependency on the rolling balls depends on the intensity of the external load (Figure 2 - Figure 3) in the function of the radial clearance.

By analysing the obtained results and the diagrams presented it is concluded that increasing the intensity of the external radial load linearly increases the load values transmitted by the rolling elements of the bearing. It can be seen that increasing radial clearance increases the value of force on the site of the most loaded balls and reduces the loads of other balls involved in the distribution. This increases the unbalance of the load distribution on the rolling elements as the overall contact deformation increases on the site of the most loaded balls and reduces the contact deformations of the joined parts at the spots of the other balls. For the sake of clarity, on the diagrams, a dashed line represents the load value that the rolling elements transpose when ball bearing has no clearance.

Theoretically, in the case of large internal radial clearance in the bearing and at certain external loads, the load distribution on the ball bearing rolling elements is very unfavorable, regarding the expected balls do not come in contact, so that a large part of the external load is transmitted by the ball at line of attack force. Only after the great contact deformation of the coupled parts comes the contact of the other rolling elements.

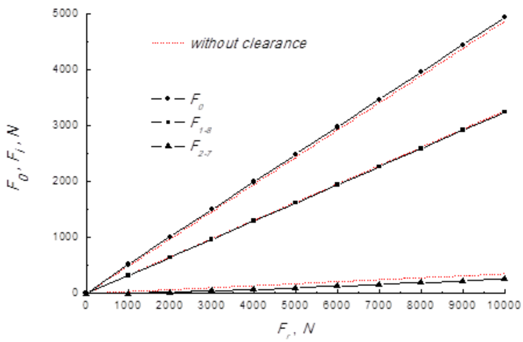

Figure 2. Load distribution on ball bearing rolling elements of 6206 depending on external load, in case of bearing with internal radial clearance (e=10 µm)

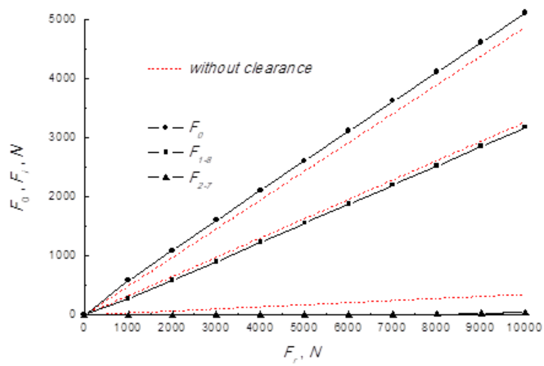

Figure 3. Load distribution on ball bearing rolling elements of 6206 depending on external load, in case of bearing with internal radial clearance (e=20 µm)

Table 2 gives the results of factor of uneven load distribution in the function of radial clearance e.

Table 2. Factor of uneven load distribution for ball bearing 6206

e	Results	F_r, N				
μm		1000	3000	5000	7000	9000
0	k	4.385	4.385	4.385	4.385	4.385
10		4.838	4.631	4.562	4.528	4.507
20		5.236	4.823	4.712	4.657	4.620
30		5.632	5.015	4.849	4.767	4.716

Based on the presented solutions, diagrams of factor changes of balls uneven load distribution in function of the inner radial clearances are given (Figure 4). The figure shows that the values of the factor k = 5 correspond to the radial clearance $e \approx 29\mu m$ (at a given external load, eg F = 3000 N), and that for other values of the clearance it changes (bigger or smaller). It is concluded that for the different clearances values the same value of factor of uneven the load distribution on balls k = 5, as it appears in the literature [4], can't be taken but the actual value (calculated values given in the table). This is especially important when designing bearings and supporting elements in general when the analysis of load distribution plays an important role. Taking into account the actual value of factor k it is possible to determine more precisely the static bearing load. For the sake of visibility the curvature depends only on the external load in the interval $F_r = 1000 \div 5000N$.

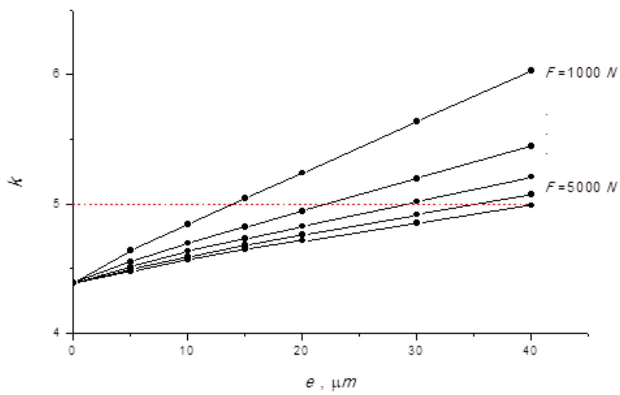

Figure 4. Change of factor of uneven load distribution to the ball bearing rolling elements in function of the radial clearance, and for the given external load

3. THE CHOICE AND MODELLING OF SIMPLIFIED REAL AND FEM MODELS OF SINGLE ROW DEEP GROOVE RADIAL BALL BEARING FOR ANALYSIS OF LOAD DISTRIBUTION OF BALL BEARING ROLLING ELEMENTS

In Figure 5, a 2D plane mesh model of finite elements for single row radial ball bearing 6206, which has nine balls, is given (the worst moment is shown when one of the balls is on the attack line of the given external load). For the discretization of the 2D physical model, 2D four-node isoparametric finite elements were used. During generalization of 2D mesh of finite elements a plane state is chosen (it is assumed that in all cross-sections of bearing the stress distribution is the same) as well as very precise division of finite elements mesh.

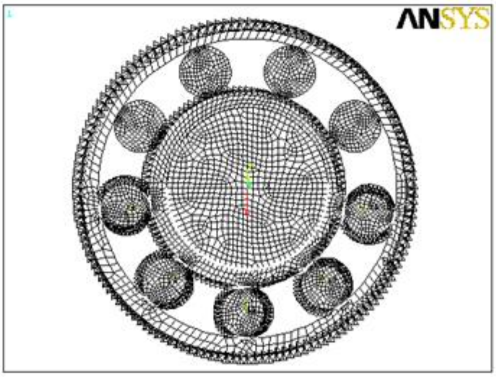

Figure 5. The mesh of 2D finite elements for the model of radial bearing 6206 with defined contact finite elements, boundary conditions (twisted coordinate system) and external load

Model of the bearing is presented in x-y global Descartes' coordinate system with its ground zero in axis of inner bearing ring. Balls bearing have local coordinate systems. Ball that is in the line of offensive force (line of y-axis) has the same coordinate system as global model bearing system with its ground zero in the centre of the ball. Other balls have twisted coordinate systems compared to the global one with its ground zero placed in the center of them. For the sake of simplified simulation of load and data observing the model is set in such a way that external load is given in the line of y-axis (radial direction). Thus the total contact deformation of the most stressed ball (the relative displacement of bearing) could be seen from results obtained from FEM analysis as node displacement in the direction of y-axis of global coordinate system. Outer bearing ring is absolutely immobilized (boundary conditions are given so that displacement is not allowed neither in line of x-axis nor y-axis). Inner bearing ring is limited in line of x-axis that is its displacement is allowed in the line of external load. The ball placed in the line of external load has exactly the same boundary conditions as inner bearing ring. The limitations of the balls in the line of external offensive line are given in radial twisted coordinate systems. Boundary conditions are given so that imitate the cage where balls are placed in the real environment. The displacement is allowed in the radial direction (direction that connects the center of model bearing to appropriate balls center). In the perpendicular direction in the radial axis of twisted coordinate system, the displacement equals zero. Without boundary conditions defined that way balls were simply sliding along model during experiment (by giving them the external load). Nodes placed in expected contact zone of balls with outer and inner bearing ring have no boundary conditions. External radial load is given in the ground zero of global coordinate system of bearing model and variates from 1000 up to 5000 N.

The results error obtained by FEM is less than 10% compared to theoretic results.

From figure 6, the distribution of the given external radial load to the ball bearing rolling elements for the case of ball bearing without internal radial clearance is clearly visible. The most loaded ball in the bearing is ball in the direction of the action of the external load then the balls left and right of the most loaded ball. Balls right below the meridian plane are the least involved in the distribution of loads. It should be emphasized that the load values distribution by the corresponding balls left and right from the most loaded are equal which is another indication of the validity of the adopted numerical bearing model.

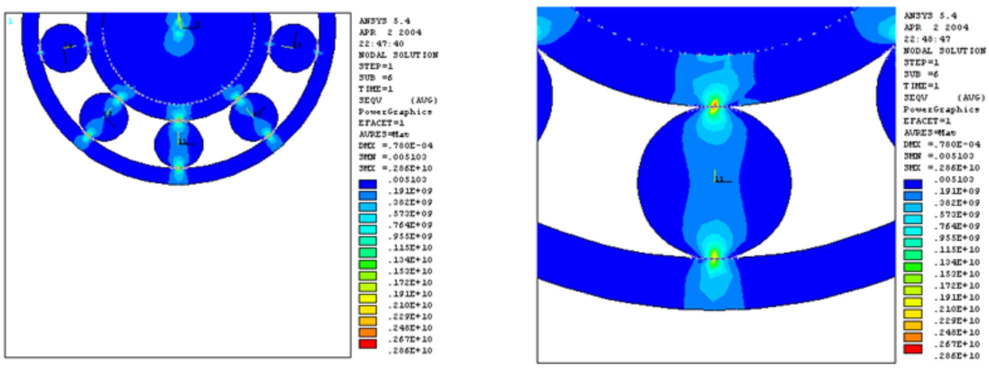

Figure 6. Numerical results of load distribution on ball bearing 6206 under the external radial load for the case of ball bearing without internal radial clearance

In Figure 7 and 8, the influence of the inner radial clearance on the load distribution is obvious. As obtained from the analytical calculation and numerical models results have been confirmed that balls located just below the meridian plane (and farthest from the most loaded ball for the given external loads) do not come into contact until a large contact deformation occurs.

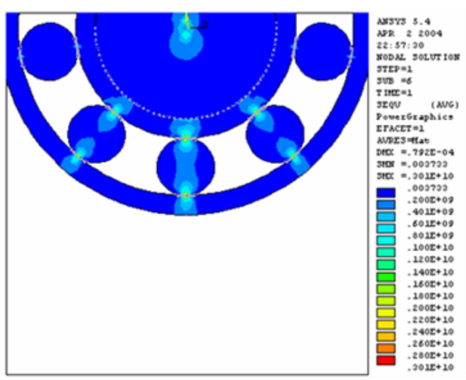

Figure 7. Numerical results of load distribution on ball bearing 6206 under the external radial load for the case of ball bearing with internal radial clearance

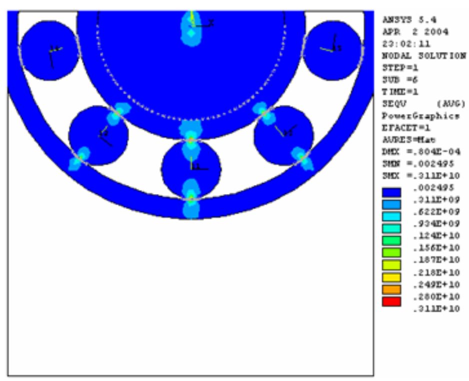

Figure 8. Numerical results of load distribution on ball bearing 6206 under the external radial load for the case of ball bearing with internal radial clearance

$e \approx 10\mu m$ $e \approx 20\mu m$

For the additional verification of the accuracy of numerical solutions, a case in the literature was provided, bearing 6306, the results of which were compared with the available theoretical [4] and numerical [5] solutions. The appearance of the 2D model of the finite elements of the radial ball bearing 6306 and the boundary conditions are identical to the bearing 6206 whose words are already detailed. Figure 9 clearly shows that results obtained by using FEM described above are more than satisfactory. Results error of FEM analysis compared to theoretic data is less than 1% (note: results are obtained by giving the external load on 6306 bearing). Comparison of the results obtained by both, ANSYS and I-DEAS Supertab softwares, demonstrate that numeric results of ANSYS are more precise to theoretic data [4] than that of I-DEAS Supertab [5].

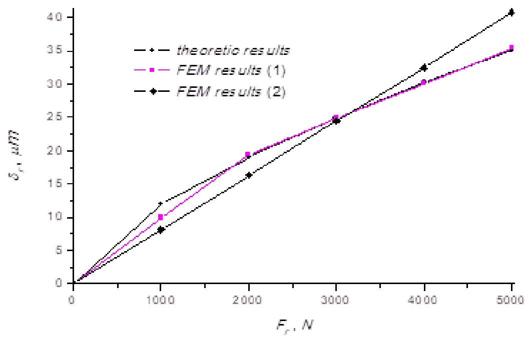

Figure 9. Graphic demonstration of the results comparison (total radial axis displacement of 6306 bearing and intensity of external load are compared) according: Theoretic research, FEM analysis by using of I-DEAS Supertab software -curve (2), [5] and FEM analysis by using of ANSYS software - curve (1)

4. CONCLUSIONS

Due to the complexity of the problem the numeric model of the ball bearing mentioned above is developed. The Finite Element Method is the numerical method used. Software used is ANSYS v.5.4. The choice and modelling of single row radial ball bearing for load distribution on ball bearing elements and stress deformation state analysis is detailed in literature. Obtained results confirmed the theoretic approach to the problem of load distribution on ball bearing elements analysis (the error of obtained results compared to the theoretic ones did not excess 10%). The same approach of ball bearing modelling could be applied to other series and ball bearing types as well. The future exploration of this problem will be directed to 3D modelling and obtaining the most reliable results possible.

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