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Analysis of the Influence of Large Diameter Bearing Support Structure Condition on Reliability in Operation

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The causes of support structure deformation of the large diameter bearing arise from external loads and they are variable by the magnitude and point where load acts. By forming a model of bonds, on the basis of which would be performed a theoretical analysis of the interaction of revolving and non-revolving parts in construction and transport mechanization machines, with the variation of geometric values of supporting structure elements, could be obtained some parameters that have a dominant influence on the increasing of necessary support surface stiffness for bearing bond. Therefore, the deformation of support surface must be smaller than allowed value. In this way, will be separated a typical carrying structures which favorably effect on functionality of bonds. Also, we noticed the shortcomings of these structures that should be eliminated. The result of such research and analysis should enable the fulfillment of the demands which placed before of construction and transport mechanization machines, i.e. the better adaptability of the excavator running machine with the leaning surface, as well as the radial-axial bearing support surface deformation must be kept under the limits that allows the proper functioning of bonds.

Key words: support surface, radial-axial bearing, deformation, influence parameters

1. INTRODUCTION

The basic characteristic of revolving and non-revolving parts bond with radial-axial bearing, i.e. the basic prerequisite for proper functioning and the mounting of this type of bearing, is certainly a requirement for greater precision and quality of support surface. Of course, the need for always flat a support surface on one side and the proper functioning of the bond on the other side make it an absolutely justified a precise machining of the support surface.

Before mounting of large diameter bearing, there is recommendation for measuring of support surface with appropriate optical or laser measuring devices (Fig. 1a). If the measured values exceed the values that are allowed a proper functioning, there is recommendation for additional machining, with portable machines (Fig.1b). Of course, in some cases, additional machining of support surface can lead to difficulties, and for exceptional cases where the previously described procedure could not be applied, there is the possibility for further consulting with the manufacturer and for removing the irregularity of the support surface.

Bearing in mind all the previously mentioned facts, of course with other requirements for the normal functioning of bearings (thermal and finely machining of surfaces for balls and rollers rolling, precise machining of the parts for which the bearing is attached, the stiffness of the supporting structure, etc.), it is necessary to analyse the influence of the condition of support surface, all in order to achieve the final goal - to increasing the safety and reliability of revolving and non-revolving bonds in construction and transport mechanization machines.

The deformation of bearing support surface must be smaller than $\delta=r\cdot 10^{-4}$ [1], where r is the bearing radius.

If this condition is not met, the proper functioning of the revolving and non-revolving parts bond is disabled, i.e. there is occurred a no uniform distribution of the axial force to the indirect elements of the bearing.

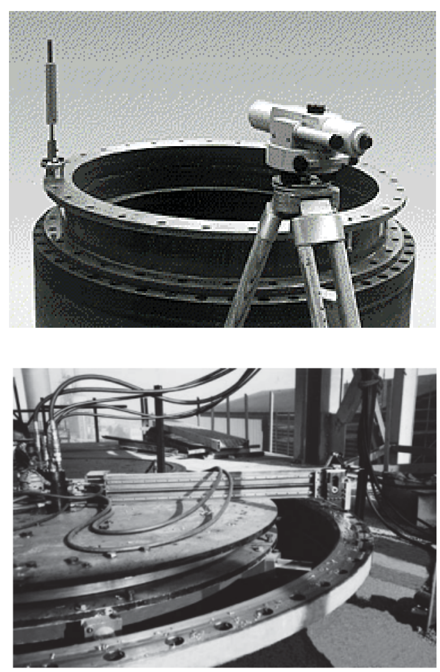

Fig.1. Measuring and machining of large diameter bearing support surface [11]

The recommendations of the bearing manufactures for support surface deformation (Fig.2), which depends from the type of radial - axial bearing and the bearing radius, are shown in Table 1. [11].

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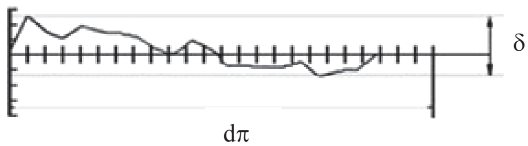


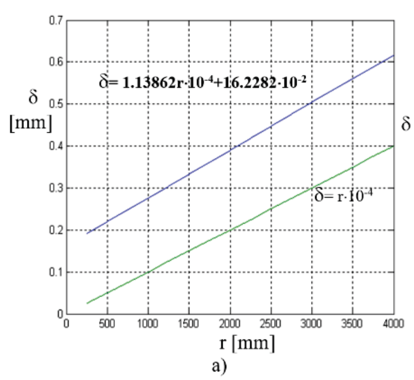
Fig. 2. Radial-axial bearing support surface deformation [11]

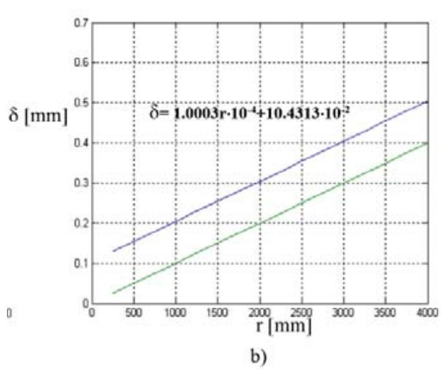
Table 1. Allowed values of radial-axial bearing support surface deformation

Radius r (mm)	Support structure deformation δ (mm)		
	Two-way ball bearing	One-way ball bearing	Roller bearing
250	0.15	0.10	0.07
500	0.20	0.15	0.10
750	0.25	0.19	0.12
1000	0.30	0.22	0.15
1250	0.35	0.25	0.17
2000	0.40	0.30	0.20
3000	0.50	0.40	0.30
4000	0.60	0.50	0.40

Analyzing these recommendations as essential for the proper functioning of revolving and non-revolving parts bond, the support surface deformation in the function of the bearing radius can be shown graphically, so that on the basis of that comparative diagrams a certain conclusions could be obtained about a influencing of the support surface condition on proper functioning of radial-axial bearing.

Comparative diagrams for different types of bearings are shown in Figure 3.





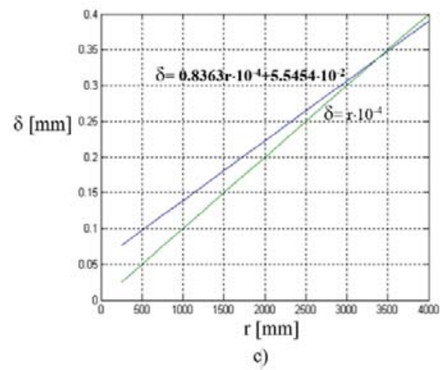


Fig. 3. Deformation - bearing radius comparative diagrams: a)two-way ball bearing; b) one-way ball bearing; c) roller bearing

With comparative analysis of the diagrams and functional dependencies of the support surface deformation and bearing radius with the function $\delta = r \cdot 10^{-4}$ for two-way ball bearing ($\delta = 1.13862r \cdot 10^{-4} + 16.2282 \cdot 10^{-2}$), single-row ball bearing ($\delta = 1.0003r \cdot 10^{-4} + 10.4313 \cdot 10^{-2}$) and roller bearing ($\delta = 0.8363r \cdot 10^{-4} + 5.5454 \cdot 10^{-2}$), some global conclusions are obtained:

- The function $\delta = r \cdot 10^{-4}$ allows a greater degree of reliability of the proper bond functioning, i.e. there is more stringent requirements that the support surface must satisfy for the proper bond functioning;

- Requirements that are placed before the surface depending of the type of bearing, so with the construction of the bearing itself it is possible to provide greater allowed displacement of the support surface;

- For the first two types of bearings, it can be seen that the slope of lines is the same, and different for the third type, which corresponds only to the fact that, except for the construction of the bearing itself, we can achieve the permissible displacement of support surface with the fulfillment of other conditions, i.e. by achieving the required stiffness of the bearing carrying structure itself. In other words, the roller bearing requires the greatest value of stiffness of supporting structure.

For further analysis of this problem, in this paper, it is necessary to forming a calculation model and analysing the influence of certain parameters (the condition of the path by which the balls moves, the supporting structures, etc.) to the support surface deformation, in order to reduce the influence of the previously mentioned parameters, as well as the fulfillment of requirements imposed before construction and transport mechanization machines (the better adaptability of the running machine with the leaning surface, i.e. the full contact of all the wheels with the track, and in that case the radial - axial bearing deformations could not exceeds the values that enable a proper bond functioning.

2. FORMING A CALCULATION MODELS

Basically, the excavator carrying structure is a statically indeterminate system, and as previously indicated [9], the displacement one of the frame supports in that systems makes their deformations and creates stresses in the structural elements, so that structure during the displacement of supports is additionally loaded or unloaded.

In addition to the force method of analysis, statically indeterminate systems can also be solved by the displacement method, which is based on a completely different concept in relation to the force method. In this case, basic displacements of the joints caused by external load, are unknown.

In order to eliminate all joints deformation degrees of freedom (rotation and translation), additional bonds are introduced. In this way, the basic system is formed, i.e. the dividing (discretization) of the continuous structure into simpler characteristic elements is obtained, which behavior as the independent element exposed to bending is known.

In the matrix form, the system of canonical equations, for the basic system with several kinematic unknowns, is:

$$[r] \cdot \{Z\} + \{R_F\} = \{0\} \tag{1}$$

where are:

- r - matrix of influential coefficients of stiffness (matrix of reactions due to unit displacements);

$$[r] = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ . & . & \cdots & . \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix}$$

- Z -vector of unknown dispacements;

$$\{Z\} = \begin{Bmatrix} Z_1 \\ Z_2 \\ . \\ . \\ . \\ Z_n \end{Bmatrix}$$

- R_F -vector of reaction causes by given loads.

$$\{R_F\} = \begin{Bmatrix} R_{1F} \\ R_{2F} \\ . \\ . \\ . \\ R_{nF} \end{Bmatrix}$$

Formation of the basic system (Fig. 4) is always done in the same way, which is the advantage of the displacement method in relation to the force method.

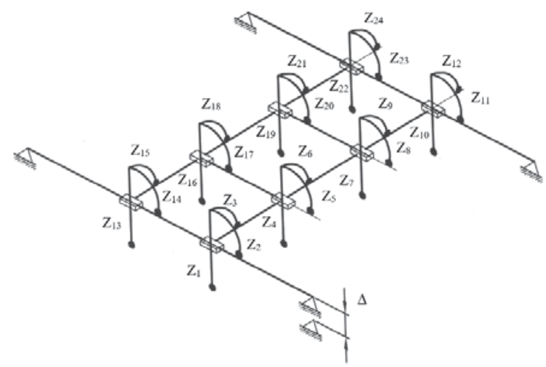


Fig. 4. The basic system of excavator carryng frame (H-type)

The moment diagrams in the basic system from given displacement of the support Δ and unit displacements $\bar{Z}_i=1$ (i=1,2,…,24), are shown on Fig. 5 and 6). According to these diagrams, with isolating of joints or certain frame parts and solving a equilibrium equations, are determined r_{ij} i $R_{j\Delta}$ (i,j=1,2,…,24).

The canonical equations of the displacement method in the case when the given load is the displacement one of the supports, in the general form are:

$$\sum_{j=1}^{24} r_{ij} \cdot Z_j + R_{j\Delta} = 0 \quad ; \quad i = 1,...,24 \tag{2}$$

where are $R_{j\Delta}$ (j=1,…,24) reactions at the place of the attachment bonds in the base system due to the displacement of the supports.

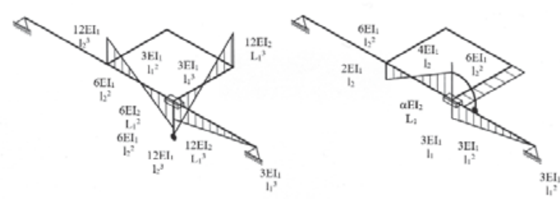


Fig. 5. The moment diagrams of the basic system from $\bar{Z}_i=1$, (i=1,2)

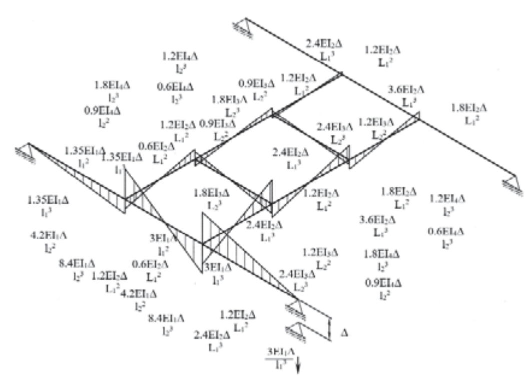


Fig. 6. The moment diagrams in the basic system from displacement Δ

The influential stiffness coefficients on the main diagonal (the main reactions) are always positive, while the van diagonal members are symmetric (r_{ij} and r_{ji}) and can be both positive and negative. It is important to note that the moment diagrams due to movement are obtained when the ordinate of the moment specified for the unit displacements is multiplied by the actual displacement values.

Considering the number of reactions introduced in joints, the procedure is shown for example of joint 1 (to which corresponds the kinematic unknown Z_1, Z_2 and Z_3). Isolating a joint 1 from the structure (Fig.7), reactive moments and forces should change the directions, while the r_{ij} have the assumed direction in accordance with the assumed directions Z_1, Z_2 and Z_3. Accordingly, the values of the reaction are given in Table 2.

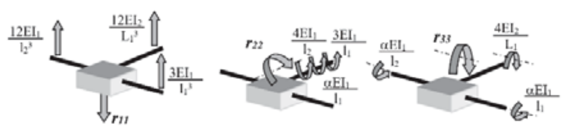


Fig. 7. The values of reaction (r_{11},r_{22} i r_{33})

Observing the expressions for the values of reactions introduced at the places of fixed ends (Table 2), and according to the previously mentioned feature of indeterminate systems, the presence of bending and torsional stiffness is noticeable, i.e. their relationship $\alpha = \frac{GI_0}{EI}$, [3].

In order to facilitate the generalization of the expression, it is necessary to introduce the relation between the bending and torsional stiffness of the box-shaped cross-section of the excavator carrying structure. The relation between the bending and torsional stiffness, for the realized excavator carrying structure can be shown in the function of the ratio of width and height of the same [3,9]. Starting from the expression:

$$EI = \sqrt{3}\frac{h}{b}GI_0 \tag{3}$$

we get:

$$\frac{EI}{GI_0} = \sqrt{3}\frac{h}{b} \Rightarrow \frac{1}{\alpha} = \sqrt{3}\frac{h}{b}$$

$$\alpha = \frac{\sqrt{3}b}{3h} = 0.57735\frac{b}{h}$$

If obtained relationship as well as the realized solution characteristics of the excavator carrying structure are used, it is possible to obtain the reactions and unknown displacements in terms of the carrier width and height ratio and the support displacement Δ causes by external load (Table 2).

Table 2. The reaction values in general form

$R_{j\Delta}$	General form of $R_{j\Delta}$	Value x [$\Delta \cdot 10^3$]
$R_{1\Delta}$	$\Delta\left(\frac{8.4EI_1}{l_2^3}+\frac{8.4EI_2}{L_1^3}-\frac{6EI_1}{L_1^3}-\frac{3EI_1}{l_1^3}\right)$	7.83940
$R_{2\Delta}$	$\Delta\left(-\frac{4.2EI_1}{l_2^2}-\frac{3EI_1}{l_1^2}\right)$	-407.046937
$R_{3\Delta}$	$\Delta\left(\frac{4.2EI_2}{L_1^2}-\frac{3EI_2}{L_1^2}\right)$	77.312761
$R_{4\Delta}$	$\Delta\left(\frac{6EI_2}{L_1^3}+\frac{6EI_3}{L_2^3}+\frac{6EI_3}{l_2^3}-\frac{8.4EI_2}{L_1^3}-\frac{4.2EI_4}{l_2^3}-\frac{3.6EI_3}{L_2^3}\right)$	0.6451896
$R_{5\Delta}$	$\Delta\left(\frac{2.1EI_4}{l_2^2}-\frac{3EI_4}{l_2^2}\right)$	-47.622093
$R_{6\Delta}$	$\Delta\left(\frac{4.2EI_2}{L_1^2}-\frac{3EI_2}{L_1^2}+\frac{3EI_3}{L_2^2}-\frac{1.8EI_3}{L_2^2}\right)$	140.8088
$R_{7\Delta}$	$\Delta\left(\frac{3.6EI_3}{L_2^3}+\frac{3.6EI_2}{L_1^3}+\frac{6EI_4}{l_2^3}-\frac{4.2EI_4}{l_2^3}-\frac{6EI_3}{L_2^3}\right)$	2.8022979
$R_{8\Delta}$	$\Delta\left(\frac{1.2EI_4}{l_2^2}-\frac{1.8EI_4}{l_2^2}\right)$	-31.7480625
$R_{9\Delta}$	$\Delta\left(\frac{3EI_3}{L_2^2}+\frac{1.8EI_2}{L_1^2}-\frac{1.8EI_3}{L_2^2}\right)$	179.4652665
$R_{10\Delta}$	$\Delta\left(-\frac{3.6EI_2}{L_1^3}\right)$	-3.1991487
$R_{11\Delta}$	0	0
$R_{12\Delta}$	$\Delta\left(\frac{1.8EI_2}{L_1^2}\right)$	115.9691415
$R_{13\Delta}$	$\Delta\left(\frac{5.4EI_2}{L_1^3}+\frac{1.35EI_1}{l_1^3}-\frac{8.4EI_1}{l_2^3}-\frac{4.2EI_2}{L_1^3}\right)$	-5.34261103
$R_{14\Delta}$	$\Delta\left(-\frac{4.2EI_1}{l_2^2}-\frac{1.35EI_1}{l_1^2}\right)$	-336.8113875
$R_{15\Delta}$	$\Delta\left(\frac{2.7EI_2}{L_1^2}-\frac{2.1EI_2}{L_1^2}\right)$	38.6563805
$R_{16\Delta}$	$\Delta\left(\frac{4.2EI_2}{L_1^3}+\frac{4.2EI_3}{L_2^3}+\frac{4.2EI_4}{l_2^3}-\frac{8.4EI_2}{L_1^3}-\frac{4.2EI_3}{L_2^3}-\frac{6EI_4}{l_2^3}\right)$	-1.0663829
$R_{17\Delta}$	$\Delta\left(\frac{2.1EI_4}{l_2^2}-\frac{3EI_4}{l_2^2}\right)$	-47.62209
$R_{18\Delta}$	$\Delta\left(\frac{2.7EI_2}{L_1^2}-\frac{2.1EI_2}{L_1^2}+\frac{2.1EI_3}{L_2^2}-\frac{1.2EI_3}{L_2^2}\right)$	86.278474
$R_{19\Delta}$	$\Delta\left(\frac{2.4EI_3}{L_2^3}+\frac{2.4EI_2}{L_1^3}+\frac{2.4EI_4}{l_2^3}-\frac{3.6EI_4}{l_2^3}-\frac{4.2EI_3}{L_2^3}\right)$	0.14851192
$R_{20\Delta}$	$\Delta\left(\frac{2.1EI_4}{l_2^2}-\frac{1.8EI_4}{l_2^2}\right)$	15.87403125
$R_{21\Delta}$	$\Delta\left(\frac{2.1EI_3}{L_2^2}+\frac{1.2EI_2}{L_1^2}-\frac{1.2EI_3}{L_2^2}\right)$	124.9348548
$R_{22\Delta}$	$\Delta\left(-\frac{2.4EI_2}{L_1^3}\right)$	-2.1327658
$R_{23\Delta}$	0	0
$R_{24\Delta}$	$\Delta\left(\frac{1.2EI_2}{L_1^2}\right)$	77.312761

Of course, it should be borne in mind that the moments of the inertia of the transverse carrier I_2 and the moments of the inertia of the transverse and longitudinal carrier of bearing support I_3 and I_4 are the same. On the other hand, the coefficients b_1 and b_2, which are figured in the reaction terms are shown in Table 2, represent the ratio of the width and height of the transverse and longitudinal support structure carrier. In order to further considering of the influence of the condition of leaning surface on support surface deformation, as well as the verification of the previously obtained conclusions, the realized solution of the carrying frame of the radial axial bearing with geometric parameters (Table 3) is observed (Fig. 8).

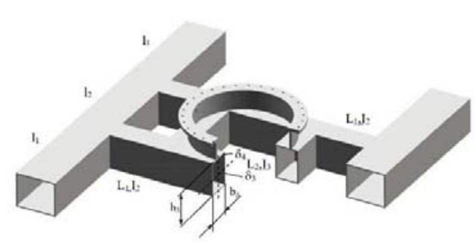


Fig. 8. Geometric parameters of realized solution of excavators carrying frame

Table 3. Geometric parameters of realized solution of excavators carrying frame [9]

Dimension	"H"
L_1 [mm]	725
L_2 [mm]	800
l_1 [mm]	1000
l_2 [mm]	800
I_1 [cm^4]	20270
I_2 [cm^4]	16126
I_3 [cm^4]	16126
I_4 [cm^4]	16126

Dimension	"H"
h_1 [mm]	300
b_1 [mm]	350
h_2 [mm]	300
b_2 [mm]	200
h_3 [mm]	300
b_3 [mm]	200
h_4 [mm]	300
b_4 [mm]	200

3. THE INFLUENCE OF ROUGHNESS OF LEANING SURFACE ON BEARING STRUCTURE SUPPORT SURFACE

In order to examine the influence of roughness of terrain by which the machine moves to the bearing support surface deformation, i.e. displacement of support surface in the direction normal to the surface, displacement of the characteristic points (Fig. 9) necessary for this type of analysis will be obtained by solving the canonical equations using the MATLAB program according to the block diagram (Fig. 10).

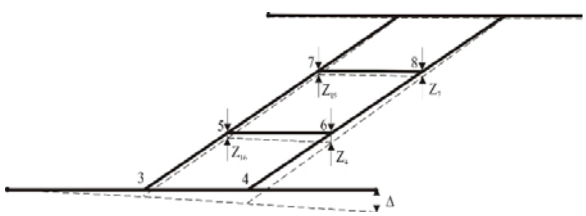


Fig. 9. The displacement of characteristic point in calculation model

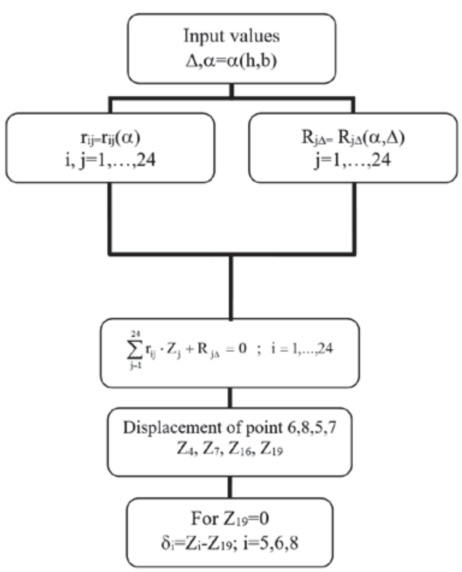


Fig. 10. Block diagram of MATLAB program

In accordance with the actual deformation of the large diameter bearings carrying or support structure, the displacement of the characteristic point with the number 7 (Fig.9) was taken for zero movement, while the relative displacements of the other characteristic points in relation to the zero could be used for determination of support surface deformation.

The results of this deformation can be obtained by solving the canonical equations system (calculation model) and by Finite Element Method (FME) (Table 4.).

Table 4. The bearing support surface deformation in relation from support displacement

Point i	FME			Displacement method- Z_i (mm)		
	Δ=5 mm	Δ=10 cm	Δ=20 mm	Δ=5 mm	Δ=10 mm	Δ=20 mm
5	1.7540	3.5079	7.0147	1.91979	3.83958	7.679168
6	2.8392	5.6781	11.356	2.60506	5.21012	10.42024
7	0.9851	1.9701	3.9397	0.93544	1.87088	3.741768
8	1.5026	3.0052	6.0094	1.39622	2.7922	5.584905

$Z_{19}=0$	β - FME (°)			β- Displacement method (°)		
	Δ=5 mm	Δ=10 mm	Δ=20 cm	Δ=5 mm	Δ=10 mm	Δ=20 mm
5	0.05506	0.110136	0.220229	0.070496	0.1409931	0.2819932
6	0.09389	0.187782	0.375576	0.0845541	0.1691079	0.3382125
8	0.03706	0.074133	0.1482310	0.0330009	0.0659846	0.1320047

The relative displacements of the support surface can also be represented by the slope of the straight line which passes through the zero and the corresponding characteristic point, i.e. rotation angle β (Fig. 11).

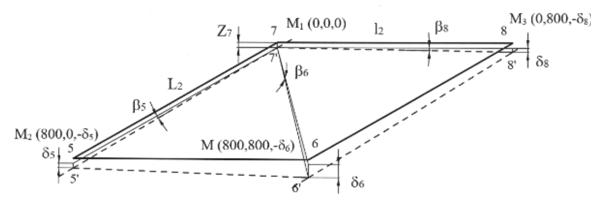


Fig. 11. Rotation of characteristic points of bearing support surface

Analyzing the results given in Tables 4, it is notable that the highest values of the angle of rotation are related to the characteristic point 6, which is in complete agreement with the actual state of the surface deformation. By moving the support of the calculation model for Δ, as previously indicated, there is a deformation or stress in the elements of large diameter bearing carrying structure. The radial-axial bearing carrying surface (Fig. 11) from position 5-6-7-8 goes to the position 5'-6'-7'-8 'in accordance with the deformation of the structure. By taking the smallest Z_7 value for zero movement, it is necessary to confirm that the displacement of the characteristic point 6 in relation to the zero along with the displacement of the other two points (5 and 8) does not belong to the same plane. Therefore, it is necessary to write a plane equation that contains three given nonlinear points M_1 (x_1, y_1, z_1), M_2 (x_2, y_2, z_2), M_3 (x_3, y_3, z_3).

Let point 6 or M (x, y, z) is an arbitrary point. It will belong to the required plane if and only if the vectors are complement, which can be written in the form

$$\left(\overrightarrow{M_1M}\times\overrightarrow{M_1M_2}\right)\cdot\overrightarrow{M_1M_3}=0\text{, or}$$

$$\begin{vmatrix} x-x_1 & y-y_1 & z-z_1 \\ x_2-x_1 & y_2-y_1 & z_2-z_1 \\ x_3-x_1 & y_3-y_1 & z_3-z_1 \end{vmatrix}=0 \quad (5)$$

If the coordinates of points are M_1 (0,0,0), M_2 (800,0,-0.98435), M_3 (0,800,-0.46078), the required equation of plane is:

$$\begin{vmatrix} x & y & z \\ 800 & 0 & -0.98435 \\ 0_1 & 800 & -0.46078 \end{vmatrix}=0 \quad (6)$$

$$787.48x+368.624y+640000z=0$$

By changing the coordinate of point M_4 (800,800, -1.66962) in the equation, the above-mentioned statement can be checked.

$$\begin{gathered}787.48x+368.624y+640000z=0\\ 787.48\cdot800+368.624\cdot800-640000\cdot1.66962=-143673.6\neq0\end{gathered} \quad (7)$$

Bearing in mind the real values of the terrain roughness and the errors that occurred during the machine construction, i.e. retaining on the smaller displacement values, the comparative diagram (Fig.12) shows the dependence between the rotation angle β of the characteristic point 6 and the displacement of the support Δ obtained by the calculation model and modeling the same structure by FME. By considering a comparative diagram, an increase in the percentage deviation obtained by two methods for the same displacement values is noticeable.

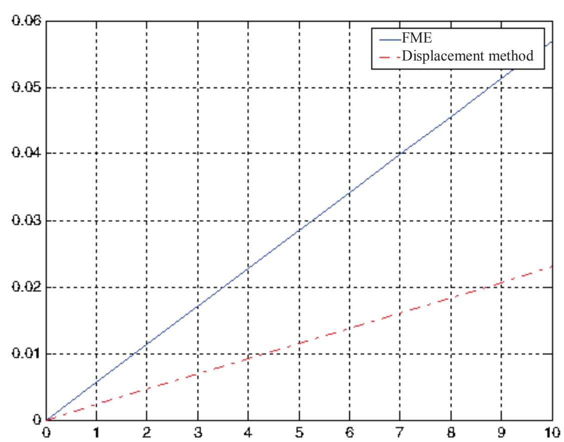


Fig. 12. Comparative diagram of releation between rotation angle β and support displacement Δ

The deviation is acceptable in view of the limitations on which the analysis was carried out on one side, while on the other hand, the facts obtained as a result of this comparative analysis coincide with the conclusion that the process of designing of large diameter bearings carrying structures, it mainly starts from numerical methods (FME), because the supporting structures are basically multi-statically indeterminate systems.

In accordance with the previous analysis, it is possible comparing an obtained value of deformation for the characteristic point 6 (the highest by value) with the values given on the comparative diagrams (Fig. 3).

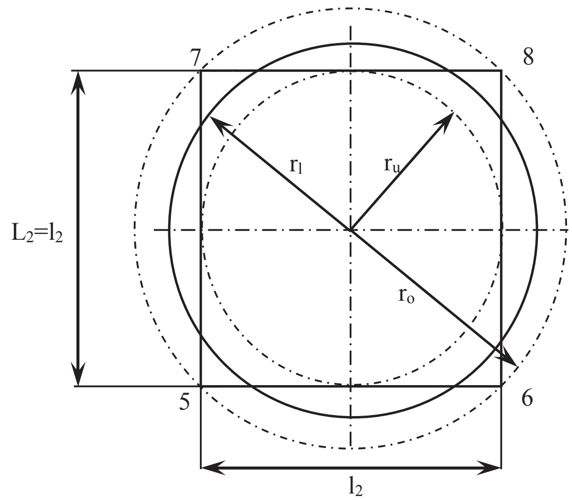


Fig. 13. The determining of bearing radius

Consequently, it is necessary to determine the bearing radius that corresponds to the supporting quadrilateral 5-6-7-8 of realized excavator carrying frame (Fig. 13). The most favorable variant is the taking of the mean value of the radius of inscribed (r_u) and described circle (r_o) of the supporting quadruple whose geometry is known. For l_2 = 800 mm, we get:

$$r_l=\frac{r_u+r_o}{2}=\frac{\frac{l_2}{2}+\frac{l_2\sqrt{2}}{2}}{2}\approx485\ \text{mm} \quad (8)$$

By comparing the deformation values (Fig.14), obtained by calculation model and the values derived from the diagrams for two types of bearings, for the radius value corresponding to the supporting quadruple, there is noticeable a higher value of deformation than the manufacturer recommendations for that bearing types. In other words, it is noticeable following facts: there is stiffness difference necessary for ensuring the proper functioning of the revolving and non-revolving parts bond, and that required difference depends from required ratio of geometric values of carrying structure and type of large diameter bearing.

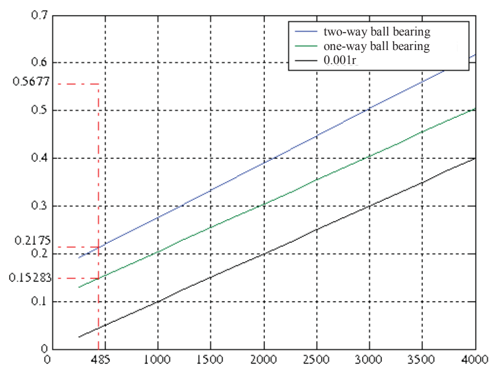


Fig. 14. Relation diagrams of deformation and bearing radius

The difference in stiffness $\Delta C = k_r \cdot C_p$, necessary for bringing the support surface under the limits covered by the bearings manufacturer's recommendations, for a same constant radius for two bearing types, and in the function of the machine support displacement Δ is shown in the Fig. 15. Where C_p is stiffness according to the manufacturer's recommendations.

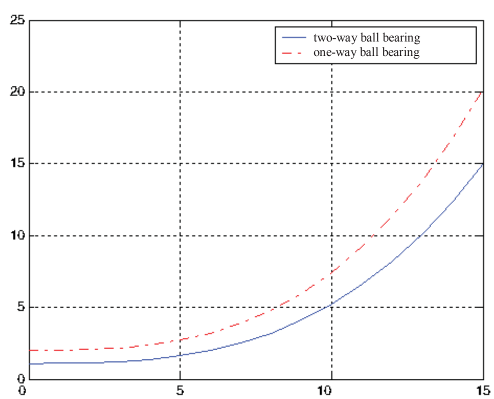


Fig. 15. Comparative diagram of stiffness difference quotient dependence kr for two bearing types

4. CONCLUSION

Drawing on the results of previous analyzes as well as the theoretical dependence obtained in this paper, it can be seen that by favoring the selection of geometric values can be achieved an increase or decrease of bearing structure stiffness itself, and consequently the support surface of the radial - axial bearing.

Naturally, it is impossible always to be completely suitable for choosing the ratio of geometric parameters, to provide sufficient stiffness, as an essential prerequisite for the normal functioning of the bond and better track supervision.

An integral element, whose installation allows to significantly influence the effect of increasing the stiffness of support surface of the radial - axial bearing, in most of the implemented solutions of construction and transport mechanization machines is a cylindrical carrier.

A cylindrical carrier, which is installed as an intermediate element between the radial axial bearing and the supporting structure itself, affects the achievement of the required stiffness, that is, contributes to and reduces the deformation of support surface. By creating an intermediate element, the effect of increasing the stiffness of the bearing support surface will be realized, i.e. the reduction in the influence of the condition of the track by which the machine moves. Bearing in mind the preconditions of reliable and safe functioning of bonds of revolving and no revolving parts, as well as a suitable choice of the ratio of the geometric dimensions of the carrying frame, it is noticeable that sufficient stiffness of the support surface can be achieved by the installation of the intermediate element as well as by the choice of the appropriate bearing type.

5. AKNOWLEGIMENTS

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