Determination of rigidity of the radial-axial bearing undercarriage frame in hydraulic excavators

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Rotating superstructure and undercarriage frame in construction machines are usually connected via large-diameter radial-axial bearing. Manufacturers of those bearings define the necessary conditions for their proper operation and a long lifetime. The main condition to be fulfilled is the necessary rigidity of the undercarriage frame of the machine, because the bearing itself, having small cross-section dimensions compared to its diameter, is not rigid enough to prevent distortion of the bearing raceway. The paper presents the analytical method for the determination of rigidity of the radial-axial bearing undercarriage frame in hydraulic excavators. A certain displacement is imposed on one undercarriage frame support which induces reactions in the others and distortion of the structure. A Maxwell-Mohr integrals and Vereshchagin rule were used to form and solve a system of canonical equations for the unknown forces and moments. The derived relations were tested by the results obtained from the finite element method analysis conducted in ANSYS package. The comparison revealed a good accuracy of the proposed model for the real-life spectrum of design parameters.

Keywords: *hydraulic excavator, undercarriage frame, rigidity, radial-axial bearing.*

1. INTRODUCTION

Rotating platforms and undercarriage frames of some building and transport machines, such as hydraulic excavators, rotor excavators, portal cranes, column cranes, are connected by radial-axial bearings having big diameters (Fig.1). Bearings manufacturers [1] define the conditions regarding their lifetime and reliability. These bearings have small dimensions of cross section in comparison to diameter, i.e. their rigidity cannot prevent distortion of the plane in which bearing elements move (balls or rolls). Thus, rigidity of undercarriage frame has to meet some conditions for reliable transfer of forces and moments when the excavator platform rotates [2], [3]. The paper analyses theoretical relations among geometrical dimensions of undercarriage frame elements which have important influence on frame rigidity.

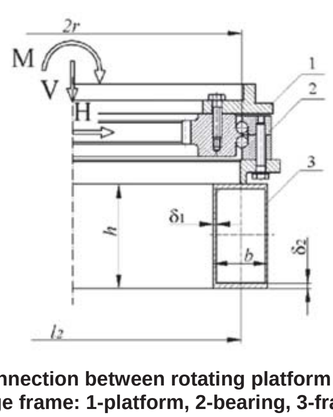

Figure 1. Connection between rotating platform and undercarriage frame: 1-platform, 2-bearing, 3-frame

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2. MODEL DEFINITION

If relations among geometric dimensions of undercarriage frame of radial-axial bearing are analysed, geometric dimensions which provide efficient distribution of load along the circumference of the bearing can be defined [4], [5] and [6].

Loads, which are transferred from rotating platform to the undercarriage frame, are shown in Fig.1. Basic geometric dimensions of cross section elements of undercarriage frame are also presented in Fig.1. When excavator is operating there is an inclination of its undercarriage structure because of the lowering of a support and pre-distribution of vertical loads, as a result of basic elements deformations. For example, if support C is lowered for value Δ, the basic system has the form presented in Fig.2, where an unknown values X_1 and X_i (i=2…7) are introduced instead of support D and rejected connections, respectively.

The system of canonical equations for the system shown in Fig.2 is:

$$A \cdot \vec{X} = \vec{\Delta} \tag{1}$$

where: A - square matrix, consisted of influential coefficients, $\vec{X}$ - vector of unknown forces and moments, $\vec{\Delta}$ - vector of free members. Influential coefficients δ_{ik} (i=1,2,...,7; k=1,2,...,7), i.e. the members of square matrix A, can be determined by Mohr's integral [7].

$$\delta_{ik} = \int_l \frac{M_{tk} \cdot M_{ti}}{G \cdot I_0} \cdot dx + \int_l \frac{M_{zk} \cdot M_{zi}}{E \cdot I_z} \cdot dx + \int_l \frac{M_{yk} \cdot M_{yi}}{E \cdot I_y} \cdot dx + \int_l \frac{N_k \cdot N_i}{E \cdot A} \cdot dx + \int_l \frac{K_z \cdot Q_{zk} \cdot Q_{zi}}{G \cdot A} \cdot dx + \int_l \frac{K_y \cdot Q_{yk} \cdot Q_{yi}}{G \cdot A} \cdot dx \tag{2}$$

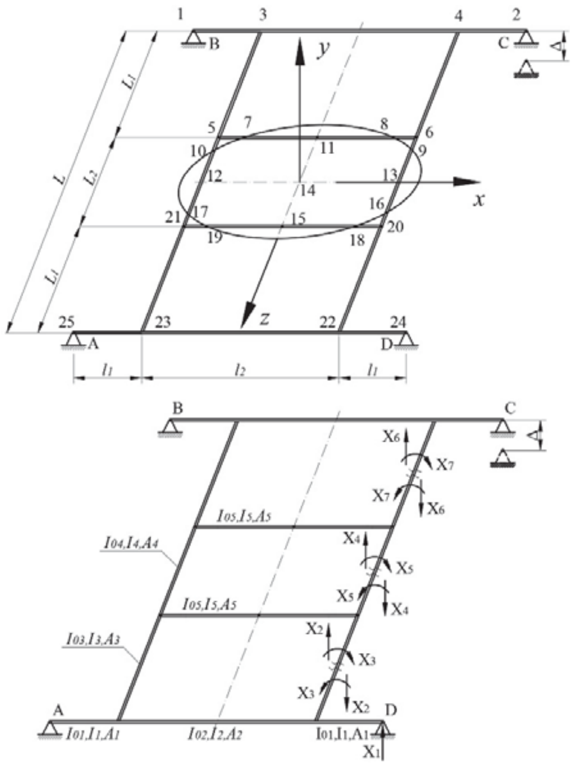

Figure 2. Model of excavator undercarriage frame

Since tension and shearing influences are far smaller than bending and torsion influences, correspondent integrals are neglected in further analysis. Vereshchagin procedure can be used to solve (2). The following relations between geometrical parameters of undercarriage frame elements are introduced:

$$\psi = L_1 / L_2;\ \eta = I_5 / I_2; \beta = I_4 / I_2; \lambda = \delta_2 / \delta_1;$$
$$\varphi = I_3 / I_2;\ w = l_1 / l_2;\ I_2 = I_1;\ k = h / b; \quad (3)$$

The system (1) is solved by program DELTA3 [8]. The following coefficients are varied: k=[1.0, 1.5, 2.0, 2.5, 3.0, 3.5], ψ=[0.0, 0.2, 0.4, 0.6, 0.8, 1.0], β=[1.0, 1.5, 2.0, 2.5], λ=[1.0, 1.5, 2.0, 2.5], φ=[1.0, 1.5, 2.0, 2.5], η=[1.0, 1.5, 2.0, 2.5], w=[0.4, 0.6, 0.8, 1.0].

3. THE INFLUENCE OF PARAMETERS ON THE UNDERCARRIAGE FRAME RIGIDITY

The analysis has been made under the following conditions:

a) constant dimensions
   - b - width of box-like member
   - δ_1, δ_2 - thicknesses of vertical and horizontal plate of box-like members
   - l_2 - distance between cross members
   - L_2 - distance between intermediate longitudinal members
   - Δ - clearance at support C.

b) constant coefficients
   - k - relation between height and width of box-like member
   - λ - relation between thicknesses of the horizontal and the vertical plates of box-like member

c) variable coefficients
   - η, β, w, φ, ψ - defined by (3).

3.1 Influence of changes of coefficient λ on rigidity of undercarriage frame

When coefficient λ is increased the rigidity of undercarriage frame is also increased. The change in relation between rigidities of undercarriage frame has the same form if λ is greater than 1.5, so these changes in relations are not presented. The influences of some characteristic parameters on the changes of rigidity of undercarriage frame are shown in Fig.3.

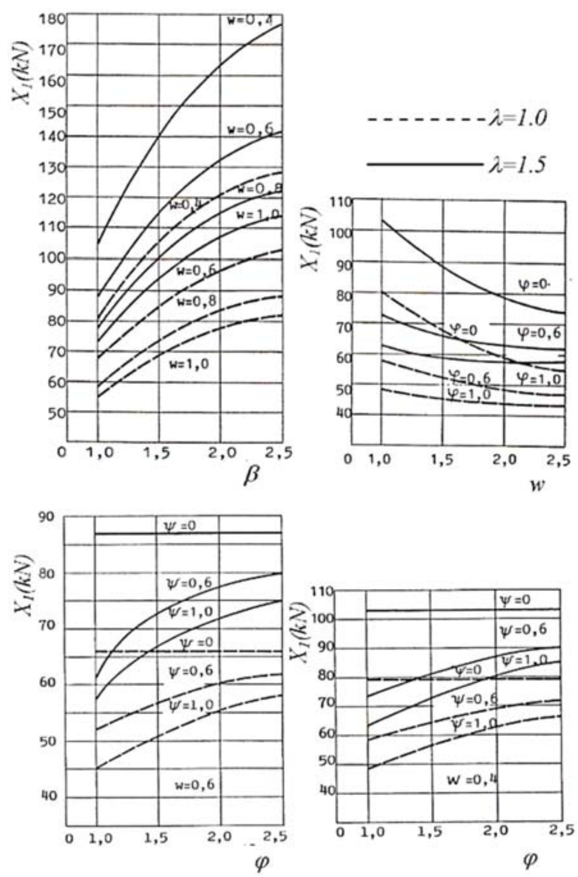

Figure 3. Change of rigidity in relation to coefficient λ

Following observations can be made on the basis of results presented in Fig. 3:

1. If coefficient β is increased, the rigidity of undercarriage frame is also increased, where maximum increase of rigidity is for β=1 ÷ 1.5;
2. If coefficient w is increased, the rigidity of undercarriage frame is decreased; the decrease of rigidity is significant for w=0.4 ÷ 0.6; for the interval w=0.8 ÷ 1 the change in rigidity is four times smaller than for the previous interval.
3. If coefficient ψ is increased, the rigidity of undercarriage frame is decreased; the decrease is almost negligible for ψ=0.8÷ 1.0.
4. If coefficient φ is increased, the rigidity of undercarriage frame is increased, whereas the slopes of the curves for the fixed value of coefficient φ are almost equal.

3.2 Influence of changes of coefficient *k* on rigidity of undercarriage frame

It is possible to define the relations between frame rigidities depending on changes of coefficient *k*. The research has been done for the following values of coefficient *k*=1.0;2.0;3.0, for different geometric characteristics of members L_2 and l_2, and for different coefficients ψ and *w*. The dependance of undercarriage frame rigidity on coefficient *k* is presented in Fig.4.

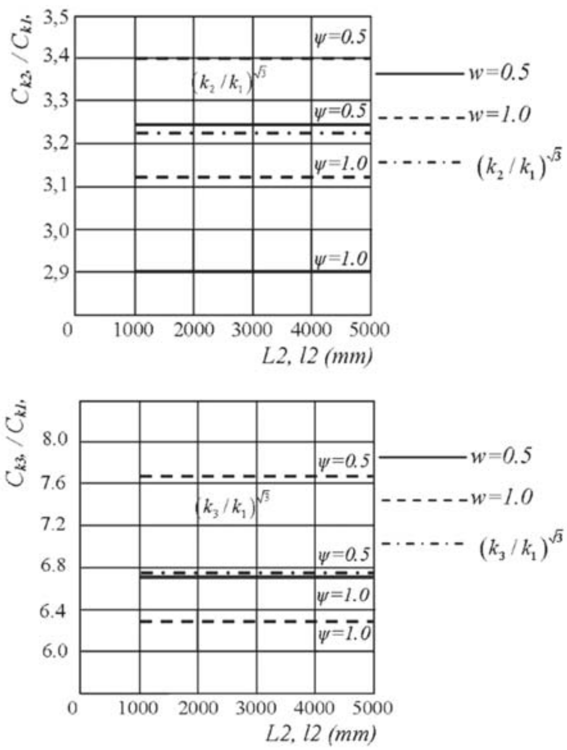

Figure 4. Change of rigidity in relation to coefficient *k*

If relation between coefficients *k* is increased, then relation between rigidities of carrying frame is also increased according to the following relation:

$$\frac{C_{ki}}{C_{kj}} = \left(\frac{k_i}{k_j}\right)^{\sqrt{3}} \tag{4}$$

3.3 Influence of changes of lengths *L* and *l* on rigidity of undercarriage frame

Tables 1 and 2 show that the increase of distance *L* for constant values of *w*, δ, *k*,λ and *b* causes the decrease of relation between rigidities of undercarriage frames according to following relation:

$$\left(C_{Li} / C_{Lj}\right) = \left(L_j / L_i\right)^3 \tag{5}$$

Table 1. The relations C_{Li}/C_{Lj}

C_{Li}/C_{Lj}	*k*=1.0; λ=1.0; *W*=0.5			*W*=1.0			$\left(\frac{L_j}{L_i}\right)^3$
	ψ=0	ψ=0.5	ψ=1	ψ=0	ψ=0.5	ψ=1	
C_{L1}/C_{L2}	8.06	8.06	8.07	8.07	8.08	8.09	8
C_{L1}/C_{L3}	27.24	27.34	27.18	27.28	27.16	27.29	27
C_{L1}/C_{L4}	65.28	64.95	64.93	64.53	64.57	64.61	64
C_{L1}/C_{L5}	127.12	127.02	126.35	127.55	127.48	125.54	125
C_{L2}/C_{L3}	3.37	3.39	3.36	3.37	3.36	3.37	3.375
C_{L2}/C_{L4}	8.09	8.05	8.04	7.99	7.99	7.98	8
C_{L2}/C_{L5}	15.77	15.75	15.65	15.79	15.77	15.51	15.625
C_{L3}/C_{L4}	2.39	2.37	2.38	2.36	2.37	2.36	2.37
C_{L3}/C_{L5}	4.66	4.64	4.65	4.67	4.69	4.60	4.629
C_{L4}/C_{L5}	1.95	1.95	1.94	1.97	1.97	1.94	1.953

Table 2. The relations C_{Li}/C_{Lj}

C_{Li}/C_{Lj}	*k*=3.0; λ=1.5; *W*=0.4			*W*=0.7			$\left(\frac{L_j}{L_i}\right)^3$
	ψ=0	ψ=0.5	ψ=1	ψ=0	ψ=0.5	ψ=1	
C_{L1}/C_{L2}	8.07	8.07	8.08	8.07	8.08	8.09	8
C_{L1}/C_{L3}	27.31	27.34	27.35	27.32	27.36	27.35	27
C_{L1}/C_{L4}	64.85	64.95	64.99	64.86	65.01	64.95	64
C_{L1}/C_{L5}	126.81	127.07	127.07	126.98	127.03	126.90	125
C_{L2}/C_{L3}	3.38	3.38	3.38	3.38	3.38	3.38	3.375
C_{L2}/C_{L4}	8.03	8.04	8.04	8.03	8.05	8.04	8
C_{L2}/C_{L5}	15.71	15.73	15.73	15.73	15.72	15.70	15.625
C_{L3}/C_{L4}	2.37	2.37	2.37	2.37	2.38	2.37	2.37
C_{L3}/C_{L5}	4.64	4.64	4.65	4.65	4.64	4.64	4.629
C_{L4}/C_{L5}	1.95	1.96	1.95	1.96	1.95	1.95	1.953

4. FINITE ELEMENT MODEL AND THE RESULTS

Finite element models for two undercarriage frames of excavators BGH600 and BGH1000 (manufactured by IMK 14. oktobar, Serbia [9]) were created to verify the derived relations from analytical model.

BGH600 undercarriage frame has the main longitudinal girders with box-like cross-section with width b_I=350mm and height h_I=300mm, so k_I=h_I/b_I=300/350=0.857. The distance between main longitudinal girders is L_I=2250mm. The same parameters for BGH1000 undercarriage frame are b_{II}=430mm and height h_{II}=330mm, so k_{II}=h_{II}/b_{II}=330/430=0.767 and L_{II}=2410mm.

FEA model was built with 2-D quadrilateral shell finite elements and the surface model was divided into fine mesh with a maximum element size of 20mm in ANSYS software, Figs. 5 and 6.

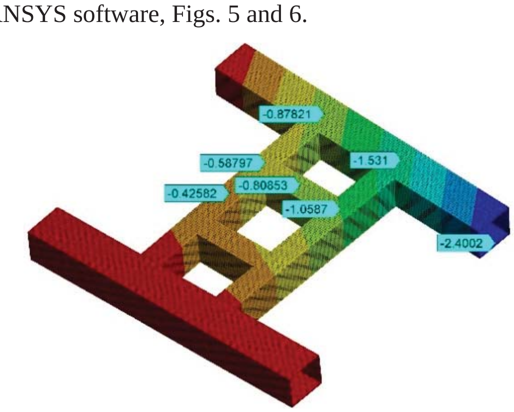

Figure 5. Displacements in FE model of BGH600

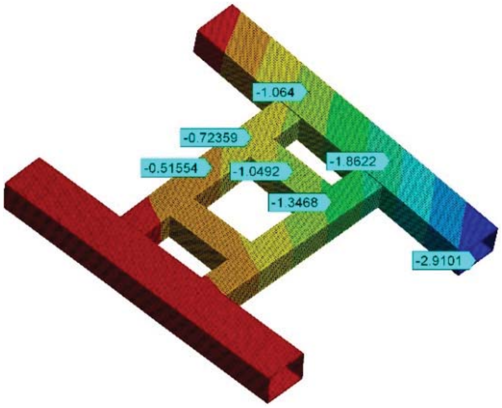

Figure 6. Displacements in FE model of BGH1000

After applying the same boundary conditions and load, the displacements for BGH600 and BGH1000 are respectively f_I=-2.4002mm and f_{II}=-2.9101mm.

If relation (5) is applied it reads:

$$\left(\frac{L_{II}}{L_I}\right)^3 = \frac{C_I}{C_{II}} = \frac{f_{II}}{f_I} \Rightarrow \left(\frac{2410}{2250}\right)^3 = \frac{-2.91}{-2.40} \Rightarrow 1.23 \cong 1.21 \quad (6)$$

If relation (4) is applied it reads:

$$\left(\frac{k_I}{k_{II}}\right)^{\sqrt{3}} = \frac{C_{kI}}{C_{kII}} = \frac{f_{II}}{f_I} \Rightarrow \left(\frac{0.857}{0.767}\right)^{\sqrt{3}} = \frac{-2.91}{-2.40} \Rightarrow 1.21 = 1.21 \quad (7)$$

Hence, derived theoretical relations were confirmed.

5. CONCLUSION

Analytical model define the influences of the geometrical dimensions and characteristic parameters of undercarriage frame on its rigidity. The most significant conclusions that were made out of many results are:

- if ratio between height and width of members of box-like cross sections is increased, the ratio between rigidities of these members are also increased; the increase of rigidity ratio is defined by ratio between coefficients k raised to a power $\sqrt{3}$;
- if a distance between axes of longitudinal girders of undercarriage frame is increased, the ratio between rigidities is decreased; ratio between frame rigidities is inversely proportional to cubic relation of distances between axes of longitudinal girders of undercarriage frame.

Derived relations are very important for continuation of research on the subject, taking into account the stiffening ring whose calculation can be performed by using the methodology presented in [10-12] and optimization of mentioned parameters [13].

These results form a good basics for proper design of the excavator undercarriage frame, providing necessary rigidity of basic surface on which radial-axial bearing is supported. The results are also important for stress analysis of the undercarriage frames and for defining the stress distribution in the frame elements.

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REFERENCES

[1] http://www.rotheerde.com//download/info/Rothe_Erde_GWL_D.pdf

[2] Smolnicki, T., Derlukiewicz, D. and Stanco, M.: Evaluation of load distribution in the superstructure rotation joint of single-bucket caterpillar excavators, Automation in construction, Vol. 17, No. 3, pp. 218-223, 2008.

[3] Kania, L.: Modeling of rollers in calculation of slewing bearing with the use of finite elements, Mechanism and Machine Theory, Vol. 41, No. 11, pp. 1359-1376, 2006.

[4] Gašić, M., Savković, M., Marković, G. and Zdravković, N.: Analysis of methods for calculating the rings of portal cranes and caterpillars, (in Serbian), IMK -14- Research and development, Vol. 30-31, pp. 37-41, ISSN 0354-6829, 2009.

[5] Makkonen, T., Nevala, K. and Heikkila, R.: A 3D model based control of an excavator, Automation in Construction, Vol. 15, No. 5, pp. 571-577, 2006.

[6] Gašić, M., Marković, G. and Savković, M.: Influence of ways of forming the excavator carrying structure on longer lifetime and better functions of radial-axial bearing, (in Rusian), International Conference INTERSTROYMEH Voronež, pp. 7-9, UDK 625.76.08, BBK 39.311-06-05+38.6-5, 2004.

[7] Borjašinov, S.V.: *Basics of structural mechanics of machines*, (in Russian), Moscow, Machine structure, 1973.

[8] Gašić, M., Ivanović, S. and Savković M.: *Program DELTA 3*, (in Serbian), Faculty of Mechanical Engineering, Kraljevo, 1989.

[9] Catalogues of Serbian hydraulic excavators manufacturers - IMK 14 October.

[10] Wong, W.C., Azid, I.A. and Majlis, B.: Theoretical Analysis of Stiffness Constant and Effective Mass for a Round-Folded Beam in MEMS Accelerometer, Strojniški vestnik - Journal of Mechanical Engineering, Vol. 57, No. 6, pp. 517-525, 2011.

[11] Smolnicki, T. and Rusinski, E.: Superelement-Based Modeling of Load Distribution in Large-Size Slewing Bearings, Journal of Mechanical Design, Vol. 129, No. 4, pp. 459-463, 2007.

[12] Gašić, M., Savković, M., Marković G. and Zdravković N.: Research and development of carrying structure of radial-axial bearing of construction and transport mechanization machines, The 6th International Symposium about forming and design in mechanical engineering - KOD 2010, pp. 41-48, 2010.

[13] Qian, Z., Xue, C. and Pan, S.: FEA agent for multidisciplinary optimization, Structural and Multidisciplinary Optimization, Vol. 22, No. 5, pp. 373-38, 2001.