Gasic M.
E-mail: gasic.m@mfkv.kg.ac.rs
Savkovic M.
Markovic G.
Zdravkovic N.
Faculty of Mechanical and Civil Engineering in Kraljevo, Serbia

Geometric identification of carrying frame of radial-axial bearing at hydraulic excavators

Abstract:

Rotating and stationary parts of some building and transport machines (excavators, portal cranes, column cranes) are connected by radial-axial bearings of big diameters which transfer not only forces but moments as well. The paper shows the research results of relations among geometric dimensions of carrying frame elements which are important for reliable functioning of the bearings. The first part of the paper deals with theoretical analysis of the influence of relations between these geometric dimensions on rigidity of the carrying frame of excavators. The second part of the paper presents the experimental analysis of changes in rigidity relation depending on characteristic parameters of realized structures of two carrying frames of excavators. Comparative analysis of theoretical and experimental results has shown a high reliability and confirmed theoretical relations defined in the paper.

Keywords: carrying frame, excavator, rigidity, bearing, experiment

0 Introduction

Rotating platform and carrying structure 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). Manufacturers who produce these bearings [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 carrying frame has to meet some conditions for reliable transfer of forces and moments when the excavator platform rotates [2] and [3]. The paper analyses theoretical relations among geometrical dimensions of carrying frame elements which have important influence on frame rigidity. These results have been verified by laboratory measurements made on the frames of realized structures.

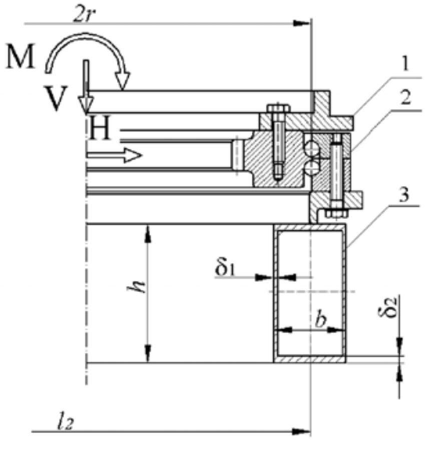

Fig.1.Connection between rotating platform and carrying frame
1. Rotating platform 2. Radial-axial bearing 3. Carrying frame of excavator

1 Model definition

If relations among geometric dimensions of carrying frame of radial-axial bearing are analyzed, geometric dimensions of carrying frame 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 carrying frame, are shown in Fig.1. Basic geometric dimensions of cross section elements of carrying frame are also presented in Fig.1. When excavator is operating there is an inclination of its carrying 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.

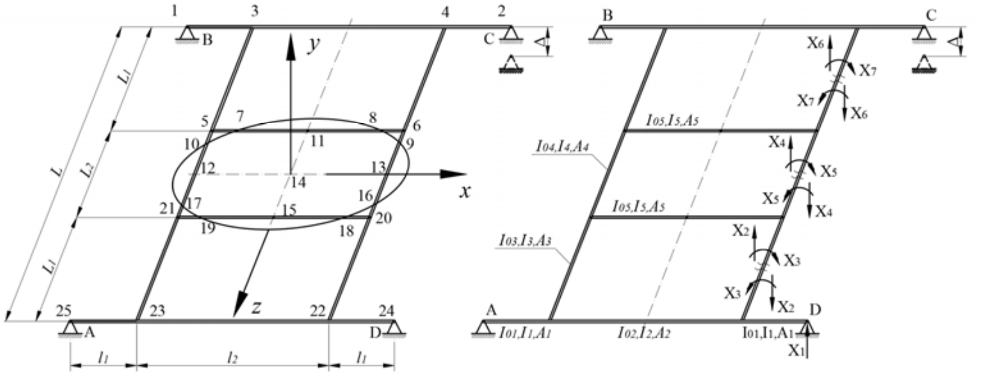

Fig.2. Model of excavator carrying frame

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)*, which represent the members of square matrix A, can be determined by Mohr's integral [7].

$$\delta_{ik} = \int_l \frac{M_{tk} \cdot M_{ti}}{G \cdot I_0} \cdot dx + \int_l \frac{M_{zk} \cdot M_{zi}}{G \cdot I_z} \cdot dx + \int_l \frac{M_{yk} \cdot M_{yi}}{G \cdot I_y} \cdot dx + \tag{2}$$

$$+ \int_l \frac{N_k \cdot N_i}{E \cdot a} \cdot dx + \int_l \frac{K_z \cdot Q_{zk} \cdot Q_{zi}}{G \cdot A} \cdot dx + \int_l \frac{K_y \cdot Q_{yk} \cdot Q_{yi}}{G \cdot A} \cdot dx$$

Since tension and shearing influences are far smaller than bending and torsion influences, the last three integrals are neglected in further analysis. Vereshchagin's procedure can be used to solve expression (2). If relation between geometrical parameters of carrying frame elements is introduced, the following relations can be defined (Fig.2):

$$\psi = L_1 / L_2; \quad \eta = I_5 / I_2; \quad \beta = I_4 / I_2; \quad \lambda = \delta_2 / \delta_1; \tag{3}$$

$$\varphi = I_3 / I_2; \quad w = l_1 / l_2; \quad I_2 = I_1; \quad k = h / b;$$

The system of canonical equations (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], δ=[10, 15, 20, 25, 30], 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].*

2 Rigidity of carrying frame depending on changes of characteristic parameters

The analysis has been made under following conditions:

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

b) constant coefficients:
   - *k* - relation between height and width of box-like member of carrying frame
   - λ - relation between thicknesses of horizontal and vertical sheets

c) variable coefficients:
   - η , β, *w*, φ, ψ - defined by relations 3.

2.1 Influence of changes in coefficient λ on rigidity of carrying frame

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

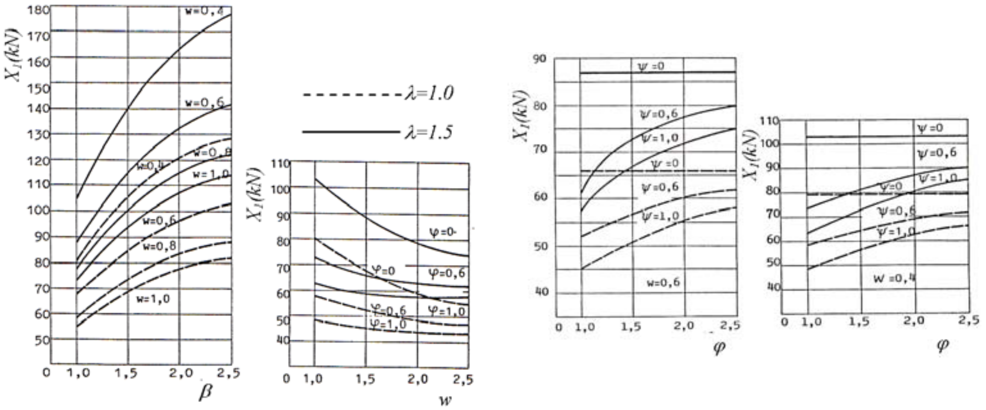

Fig.3. Influences of characteristic parameters on the changes in rigidity of carrying frame

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

1. If coefficient β is increased, the rigidity of carrying frame is also increased, but the maximum coefficient of rigidity increase is $\beta=1 \div 1.5$;
2. If coefficient w is increased, the rigidity of carrying frame is decreased. The coefficient of rigidity decrease is visible for $w=0.4 \div 0.6$. If $w=0.8 \div 1$ the change in rigidity is four times smaller than previous values.
3. If coefficient ψ is increased, the rigidity of carrying frame is decreased. Decrease coefficient is almost negligible for $\psi=0.8\div 1.0$.
4. If coefficient φ is increased, the rigidity of carrying frame is increased whereas increase coefficient is almost constant for the same value of coefficient φ.

2.2 Influence of changes in coefficient *k* on rigidity of carrying frame

It is possible to define the relations between frame rigidities depending on changes in 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. Tables 1,2,3,4,5 and 6 show the values of forces at support D with constant clearance at support C for $w=0,5$ and $w=1,0$. Fig.4 shows diagrams of changes in rigidity of carrying frame depending on coefficient k.

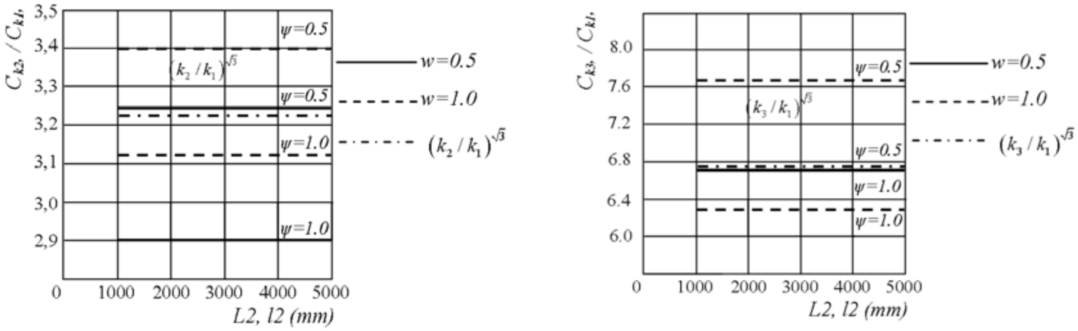

Fig.4. Diagrams of changes in rigidity of carrying frame depending on coefficient k

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

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

2.3 Influence of changes in geometrical values *L* and *l* on rigidity of carrying 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 carrying 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}*

k=1.0; λ=1.0;							
C_{Li}/C_{Lj}	*W=0.5*			*W=1.0*			$\left(\frac{L_j}{L_i}\right)^3$
	$\psi=0$	$\psi=0.5$	$\psi=1$	$\psi=0$	$\psi=0.5$	$\psi=1$	
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}*

k=3.0; λ=1.5;							
C_{Li}/C_{Lj}	*W=0.4*			*W=0.7*			$\left(\frac{L_j}{L_i}\right)^3$
	$\psi=0$	$\psi=0.5$	$\psi=1$	$\psi=0$	$\psi=0.5$	$\psi=1$	
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

3 Experiment, finite element analysis (FEA) and results

Experimental verification has been made in order to verify theoretical results which are related to the rigidity of carrying frame. The experiment has been made on two carrying frames of excavators, types BGH 600 and BGH 10000, made by IMK 14. oktobar, Serbia [9]. The carrying frames are supported by steel spheres, sets of sheet metal of various thicknesses, force transducers, basic plates lying on reinforced concrete basis. Sheet metal sets consist of plates of various thicknesses, so the clearance Δ between frame supports and steel spheres can be achieved by pulling some plates out.

Instrumentation and measuring points are shown in Figs.5 and 6, respectively.

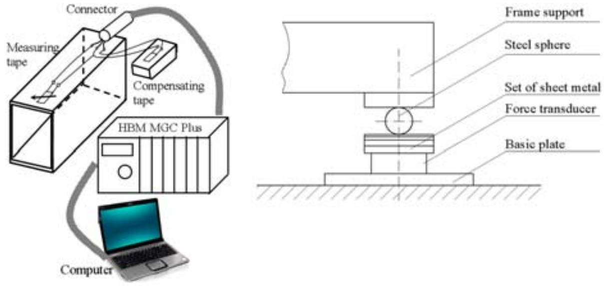

Fig.5 Measuring system and support scheme

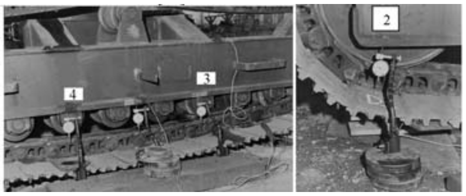

Fig.6 Some measuring points

The experiment has been made when carrying frame is supported by supports and when one of them is lowered for value Δ in comparison to other supports. The frame is loaded by the weight of rotating platform along with operating equipment and additional load [11]. Rotation has been made in each 45° A series of results have been obtained in the experiment in conformity with defined program. The paper shows the results which are significant for experimental verification of theoretical model. Thus, comparative results are obtained for displacements of characteristic points (Fig.2) of carrying frames, types BGH 600 and BGH 100. In addition, displacements for the same points were obtained from FEA, conducted in ANSYS software, Figs. 7 and 8. FEA model was built with 2-D quadrilateral shell finite elements and the surface model was divided into fine mesh with maximum element size of 20mm. The displacements for support C (point 2) (Fig.2), achieved during the experiment, were taken as an input load condition in FEA, while keeping other supports fixed. For distances *L=2250 mm* (BGH 600) and *L=2410 mm* (BGH 1000) displacements of some characteristic points are shown in Table 3. There is a high compatibility between the results from experimental testing and FEA.

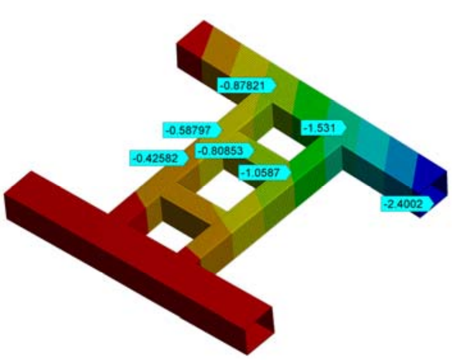

Fig.7. FEA model of BGH 600 – displacements

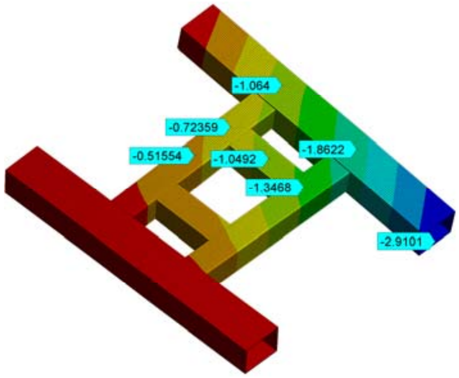

Fig.8. FEA model of BGH 1000 – displacements

Table 3. Displacements of some characteristic points (Fig.2) of carrying frame

Point number	BGH 600; L_I=2250 mm;		BGH 1000; L_{II}=2410 mm;	
	Displacements f_I (mm)		Displacements f_{II} (mm)	
	Experiment	FEA	Experiment	FEA
2	-2.40	-2.4002	-2.91	-2.9101
3	-0.91	-0.87821	-1.12	-1.064
4	-1.60	-1.531	-1.90	-1.8622
5	-0.61	-0.58797	-0.79	-0.72359
6	-1.12	-1.0587	-1.38	-1.3468
11	-0.91	-0.80853	-1.09	-1.0492
12	-0.49	-0.42582	-0.61	-0.51554

Displacements f_I and f_{II} at support 2 are important for further analysis of experimental results.
If relation (5) is applied we obtain:

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

Also, theoretical relation (4) and measurement results show high compatibility. The following relations are based on geometrical characteristics of carrying frame:

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

Therefore, theoretical relation (4) is proved, too. The obtained relations can be of great importance for continuation of research taking into account the stiffening ring whose calculation can be performed by using the methodology [12-14] and optimization of mentioned parameters [15].

4 Conclusion

Theoretical and experimental results clearly define the influence of relation between geometrical dimensions of characteristic parameters of carrying frame on its rigidity. Out of large number of obtained results only the results which are significant for defining the frame rigidity are stated:

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

These results provide forming the excavator carrying frames enabling necessary rigidity of basic surface on which radial-axial bearing is supported. The results are also important for stress analysis of the carrying frames and for defining the stress dissipation in the frame elements.

Acknowledgment

A part of this work is a contribution to the Ministry of Science and Technological Development of Serbia funded Project TR35038.

References

1. http://www.rotheerde.com/download/info/Rothe_Erde _GWL_D.pdf

2. Smolnicki, T., Derlukiewicz, D., 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., Zdravković N.: “Analysis of methods for calculating the rings of portal cranes and caterpillars“, *IMK -14- Research and development*, Vol. 30-31, pp. 37-41, ISSN 0354-6829, 2009 (in Serbian).

5. Makkonen, T., Nevala, K., 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., Savković M.: ”Influence of ways of forming the excavator carrying structure on longer lifetime and better functions of radial-axial bearing”, *International Conference INTERSTROYMEH Voronež*, pp. 7-9 UDK 625.76.08 BBK 39.311-06-05+38.6-5, 2004 (in Rusian).

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

8. Gašić, M., Ivanović, S., Savković M.: “Program DELTA 3”, Kraljevo, Faculty of Mechanical engineering,(in Serbian) from
http://www.mfkv.kg.ac.rs/index.php?option=com_content&task=view&id=82&Itemid=92.
9. Catalogues of Serbian hydraulic excavators manufacturers - ”IMK 14 October”.
10. http://www.hbm.com.pl/pdf/b0534.pdf.

11. Towarek, Z.: “Dynamics of a single-bucket excavator on a deformable soil foundation during the digging of ground”, *Mechanical Sciences*, Vol. 45, No. 6-7, pp. 1053-1076., 2003.

12. Wong, W. C., Azid, I. A., 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.

13. Smolnicki, T. 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.

14. Gašić, M., Savković, M., Marković G.,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.

15. Qian, Z., Xue, C., Pan, S.: “FEA agent for multidisciplinary optimization”, *Structural and Multidisciplinary Optimization*, Vol. 22, No. 5, pp. 373-38, 2001.