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EXPERIMENTAL DETERMINATION OF BEARING LOADS IN ROTATING PLATFORM DRIVE MECHANISMS OF HYDRAULIC EXCAVATORS

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Abstract. *The paper presents a procedure for experimental determination of slewing bearing loads in the rotating platform drive mechanisms of hydraulic excavators with an excavating manipulator. A mathematical model is defined which enables the determination of the vectors of force and moment of bearing loads, on the basis of the measured quantities of the state of an excavator in operation under exploitation conditions. The measured quantities of the state of an excavator relate to the position of the kinematic chain and pressures of the hydrostatic system in the actuator ducts of the excavator drive mechanisms. As an example, the paper provides the research results obtained in the experimental determination of slewing bearing loads in the rotating platform drive mechanism of a hydraulic excavator with the mass of 16t.*

Key Words: *Hydraulic Excavators, Rotating Platform Bearing Loads*

1. INTRODUCTION

Hydraulic excavators are mobile machines whose primary function is non-continuous excavation and transport of soil within a variable working range. The structural support of the primary function of an excavator is a kinematic chain, which comprises the following members, independently of the excavator size: support and movement mechanism L_1 (Fig. 1a), rotating platform L_2 and the manipulator with boom L_3, stick L_4 and tool L_5 – most often in the form of a bucket. In the spatial manipulation of an excavator, the rotating platform can rotate in both directions for a desired number of full rotations driven by a drive mechanism which principally comprises: a hydraulic motor 2.1 (Fig. 1b), a reducer 2.2 and a slewing bearing 2.3 [1]. The slewing bearing consists of

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outer and inner races, out of which one has a toothed edge on the outer or inner side. Between the races, in one or multiple rows, there are rolling bodies (balls, rollers) in appropriate grooves [2]. A bolted joint connects the untoothed bearing race to the frame of the rotating platform, while the toothed race is connected to the frame of the support and movement mechanism. The gear on the output shaft of the drive reducer is coupled with the toothed race of the slewing bearing, thus producing the desired rotation of the platform [3]. The manipulator drive mechanism actuators are double acting hydraulic cylinders. Former research studies connected to the rotating platform drive of hydraulic excavator are related to the dynamics of hydrostatic part drive [4] and the regulation of platform management rotation system [5] and optimal synthesis of a manipulator of mobile machines[6, 7].

Work cycles of hydraulic excavators, regardless of the size of an excavator, characteristically take place in a variable working area by cyclical repetition of the following operations: excavating the material, transporting the material from the plane of excavation to the plane of unloading, unloading the material, and returning to the plane of excavation. The aim of this paper is to determine the cycle operation in which the slewing bearing of an excavator rotating drive is subjected to the highest loading, which can be applicable to the reliable selection of the bearing.

2. Mathematical Model

In this paper, a mathematical model is developed to determine the slewing bearing loads in a platform rotating drive of hydraulic excavators, on the basis of the measured quantities of the state of the kinematic chain and excavator drive mechanisms (Table 1) (Fig. 1) when the machine operates under real-exploitation conditions.

The mathematical model covers the general five-member configuration of an excavator which consists of: support and movement mechanism L_1 (Fig. 1), rotating platform L_2, and the three-member planar manipulator with: boom L_3, stick L_4 and excavating bucket L_5. Members of the kinematic chain of an excavator create fifth-class kinematic pairs – rotary joints with a single degree of freedom. Joints axes are the axes of relative turning (rotation) of the members which constitute the kinematic pairs of the chain. The support and movement member of the excavator and the support surface create a third-class zero joint with potential movements in the plane of the surface.

The center of joint O_2 of the support member-rotation member kinematic pair is the point of perpendicular intersection of the vertical axis of the joint through the horizontal plane which contains the centers of rolling elements of the slewing bearing that connects the support and movement member to the rotation member of the chain. Centers of the manipulator joints (O_i, i = 3,4,5) are points of intersection of the axis of joints through the plane of symmetry of the manipulator chain members. The manipulator chain contained in the model of the excavator is of planar configuration. The axes of joints are parallel, while the centers of joints lie in the same plane – the plane of the manipulator. The intersection of the bucket cutting edge through the plane of the manipulator represents the center of bucket cutting edge O_w.

Table 1 Measured quantities of the state of the kinematic chain and excavator drive mechanisms

Measuring spot	Name of the measured quantity	Symbol	Dimension
*M*1	Lifting of the support and movement mechanism	c_1	*m*
*M*2	Platform rotation angle	c_2	^{o}
*M*3	Boom hydraulic cylinder motion	c_3	*m*
*M*4	Stick hydraulic cylinder motion	c_4	*m*
*M*5	Bucket hydraulic cylinder motion	c_5	*m*
*M*6	Pressure in one duct of the hyd. motor for platform rotation drive	p_{21}	*MPa*
*M*7	Pressure in other duct of the hyd. motor for platform rotation drive	p_{22}	*MPa*
*M*8	Pressure in the boom hydraulic cylinder on the piston side	p_{31}	*MPa*
*M*9	Pressure in the boom hydraulic cylinder on the connecting rod side	p_{32}	*MPa*
*M*10	Pressure in the stick hydraulic cylinder on the piston side	p_{41}	*MPa*
M11	Pressure in the stick hydraulic cylinder on the connecting rod side	p_{42}	*MPa*
M12	Pressure in the bucket hydraulic cylinder on the piston side	p_{51}	*MPa*
M13	Pressure in the bucket hyd. cylinder on the connecting rod side	p_{52}	*MPa*

The assumptions of the mathematical model of the excavator kinematic chain are:

- the support surface and kinematic chain members are modeled using rigid bodies,
- the contact between the support and movement member and the excavator support surface is taken as the first joint which has a variable position and form, thus having the form of a translatory-sliding joint along the contact between the support and movement member and the surface, while having the form of rotary joints O_{11}, O_{12}, whose axes represent potential excavator rollover lines, on the edges of the contact,
- the kinematic chain of the excavator has an open configuration, bearing in mind that even though it has a closed configuration during the digging operation, it is still observed as an open configuration chain, whose final member – the bucket, is subjected to technological digging resistances W,
- during the manipulation task, the kinematic chain of the excavator is subjected to gravitational, innate and external (technological) forces – digging resistances,
- the position of the mass center of a hydraulic cylinder is in the middle of the current length of that hydraulic cylinder,
- the influence of friction resistances is neglected in the kinematic chain and excavator drive mechanism joints.

The area of the excavator model is determined by an absolute coordinate system *OXYZ* (Fig. 1) with unit vectors $\vec{i}, \vec{j}, \vec{k}$ along the coordinate axes. The excavator support surface lies in the horizontal axis of *OXZ* absolute coordinate system, while vertical axis *OY* of the same system falls on the axis of the support member-rotating member kinematic pair when the excavator is positioned on the horizontal surface.

A member of kinematic chain L_i, in its local coordinate system $O_i\, x_i\, y_i\, z_i$, with unit vectors $\vec{i}_i, \vec{j}_i, \vec{k}_i$ along the coordinate axes, is defined by a set of geometric, kinematic and dynamic parameters [8]:

$$L_i = \{ \hat{\vec{e}}_i, \hat{\vec{s}}_i, \hat{\vec{t}}_i, m_i, \hat{J}_i \} \quad (1)$$

where $\hat{\vec{e}}_i$ is the unit vector of joint O_i axis which connects member L_i to the previous member L_{i-1} (Fig. 1), $\hat{\vec{s}}_i$ is the vector of the position of joint O_{i+1} center which is used to connect chain member L_i to next member L_{i+1} (vector s_i magnitude represents the kinematic length of the member), $\hat{\vec{t}}_i$ is the vector of the position of member L_i mass center, m_i is member mass, $\hat{J}_i$ is the tensor of the member moment of inertia.

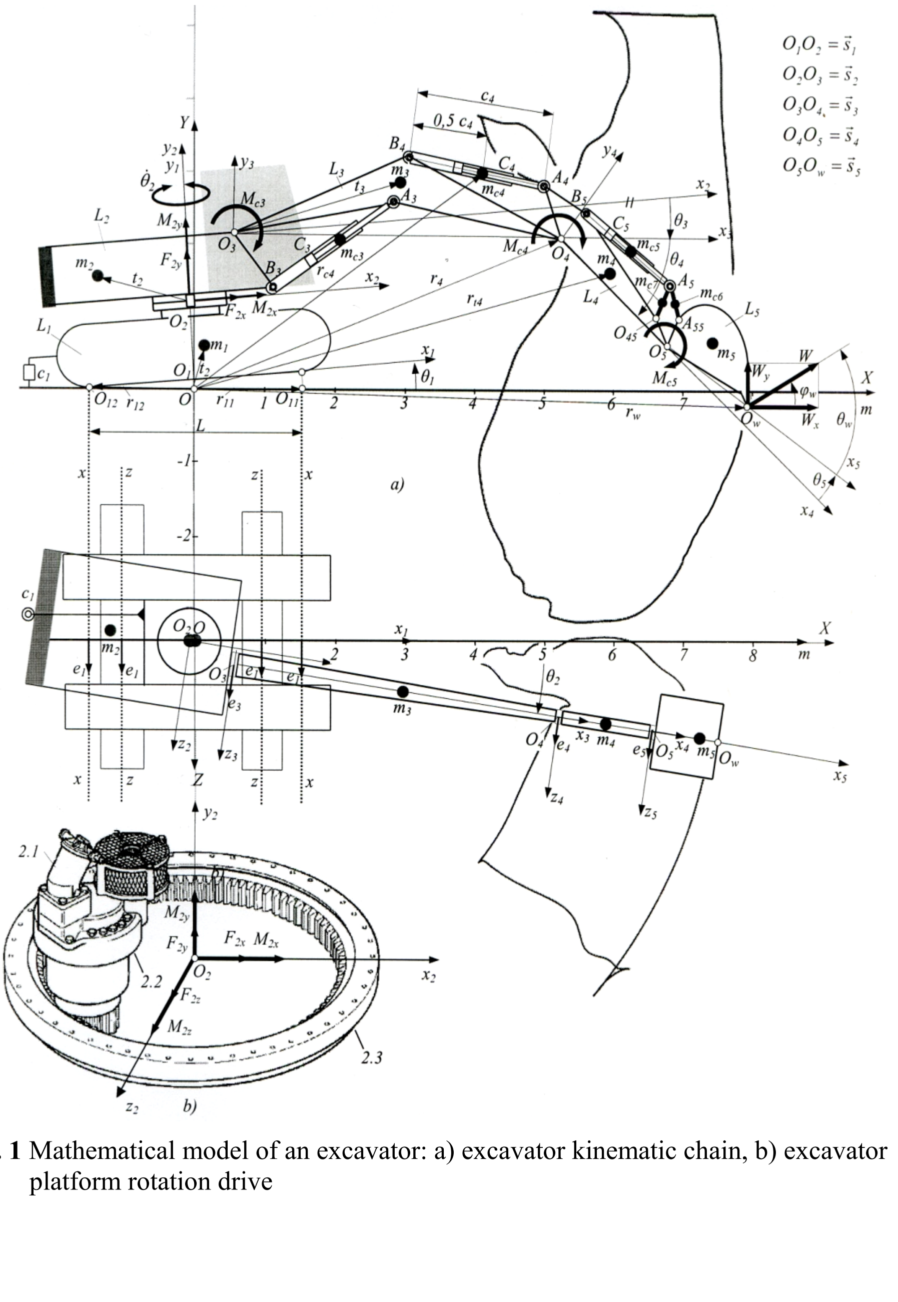

Fig. 1 Mathematical model of an excavator: a) excavator kinematic chain, b) excavator platform rotation drive

Vector quantities marked with a 'cap' relate to the local coordinate system, while those without a 'cap' relate to the absolute coordinate system. The inner (generalized) coordinates of the mathematical model of the excavator kinematic chain are represented by angles θ_i of the relative position of member L_i in relation to previous member L_{i-1} upon rotation around joint O_i axis. The lifting angle of movement mechanism θ_1 is determined on the basis of the measured relative vertical movement c_1 of the support and movement member L_1 in relation to the support surface. Angles θ_i (i=3,4,5) of the relative position of manipulator member L_i in relation to previous member L_{i-1} are determined depending on measured length c_i of the hydraulic cylinders of the manipulator boom, stick and bucket drive mechanisms [8].

Unit vector $\vec{e}_i$ of joint O_i axis of the excavator kinematic pair in the absolute coordinate system is determined by using the equation:

$$\vec{e}_i = A_{io}\hat{\vec{e}}_i \tag{2}$$

Unit vector $\vec{e}_1$ of the first joint axis is directed along potential longitudinal x-x or transverse z-z (Fig. 1) excavator rollover lines.

Vector $\vec{r}_i$ of joint O_i center of the excavator kinematic pair in the absolute coordinate system is determined by using the equation:

$$\vec{r}_i = \sum_{j=1}^{i-1} A_{jo}\hat{\vec{s}}_j \quad \forall \quad i = 2,3,4,5 \tag{3}$$

Vector $\vec{r}_w$ of the center of the bucket cutting edge in the absolute coordinate system is determined by using the equation:

$$\vec{r}_w = \sum_{i=1}^{5} A_{io}\hat{\vec{s}}_i \tag{4}$$

Vectors $\vec{r}_{ti}$ of the center of excavator kinematic chain member L_i mass in the absolute coordinate system are determined by using the equation:

$$\vec{r}_{ti} = \vec{r}_i + A_{io}\hat{\vec{t}}_i \tag{5}$$

where A_{io} is the transfer matrix used to transfer the vector quantities from local coordinate system $O_i x_i y_i z_i$ of member L_i to absolute coordinate system $OXYZ$ [8].

Kinematic quantities for the center of chain member L_i mass are: linear v_i and angular ω_i velocity and linear w_i and angular ε_i acceleration, where the movement of previous member L_{i-1} is taken as transferable, while the movement of observed member L_i in joint O_i is taken as relative.

To determine the kinematic quantities of chain member L_i in relation to the absolute coordinate system, recursive equations are used [8]:

$$\vec{\omega}_i = \vec{\omega}_{i-1} + \dot{\theta}_i\,\vec{e}_i \tag{6}$$

$$\vec{\varepsilon}_i = \vec{\varepsilon}_{i-1} + \ddot{\theta}_i\vec{e}_i + (\vec{\omega}_{i-1} \times \dot{\theta}_i\vec{e}_i) \tag{7}$$

$$\vec{v}_i = \vec{v}_{i-1} + (\vec{\omega}_{i-1} \times (\vec{s}_{i-1} - \vec{t}_{i-1})) + (\vec{\omega}_i \times \vec{t}\,) \tag{8}$$

$$\vec{w}_i = \vec{w}_{i-1} + (\vec{\varepsilon}_{i-1} \times (\vec{s}_{i-1} - \vec{t}_{i-1})) + \vec{\omega}_{i-1} \times (\vec{\omega}_{i-1} \times (\vec{s}_{i-1} - \vec{t}_{i-1})) + (\vec{\varepsilon}_i \times \vec{t}_i) + \vec{\omega}_i \times (\vec{\omega}_i \times \vec{t}_i) \tag{9}$$

where $\dot{\theta}_i, \ddot{\theta}_i$ are angular velocities and angular accelerations of member L_i in joint O_i.

Dynamic quantities of member L_i are: innate force F_i, which is determined by Newton's second law:

$$\vec{F}_i = -m_i \vec{w}_i \tag{10}$$

and the moment of innate forces M_i, which is determined by Euler's dynamic equations:

$$\hat{\vec{M}}_{ui} = -\hat{J}_i \hat{\vec{\varepsilon}}_i + (\hat{\vec{\omega}}_i \times \hat{J}_i \hat{\vec{\omega}}_i) \; ; \; \vec{M}_{ui} = A_{io} \hat{\vec{M}}_{ui} \tag{11}$$

The total force related to the center of member L_i mass, also taking into account the influence of gravity, is equal to:

$$\vec{F}_{ui} = \vec{F}_i - m_i g \, \vec{j} \tag{12}$$

Bearing in mind the assumption that the vector of digging resistance W acts in the center of the bucket cutting edge, the fictive interruption of the manipulator kinematic chain in two different joints O_i and O_j ($i \neq j$, i,j=3,4,5) can set the equilibrium conditions, for the removed chain parts, by using the equation (Fig. 1) [9]:

$$\vec{e}_i \cdot (\vec{W} \times (\vec{r}_w - \vec{r}_i)) + \vec{e}_i \cdot \vec{M}_{ri} = 0 \tag{13}$$

$$\vec{e}_j \cdot (\vec{W} \times (\vec{r}_w - \vec{r}_j)) + \vec{e}_j \cdot \vec{M}_{rj} = 0 \tag{14}$$

where $\vec{M}_{ri}, \vec{M}_{rj}$ are the resulting moments in the center of joints O_i and O_j, $\vec{r}_w, \vec{r}_i, \vec{r}_j$ - the vectors of the position of bucket cutting edge center O_w and joints O_i and O_j .

Supposing that, during the digging process, the excavator manipulator is positioned within OXY plane, the use of the previous two equations can determine the quantities of digging resistances W_x and W_y components according to the equations:

$$W_x = \frac{M_{rzi}(x_w - x_j) - M_{rzj}(x_w - x_i)}{(x_w - x_j)(y_w - y_i) - (x_w - x_i)(y_w - y_j)} \tag{15}$$

$$W_y = \frac{M_{rzi}(y_w - y_j) - M_{rzj}(y_w - y_i)}{(x_w - x_j)(y_w - y_i) - (x_w - x_i)(y_w - y_j)} \tag{16}$$

where M_{rzi}, M_{rzj} are the rotary moments around the axes of joints O_i and O_j.

The quantities of rotary moments around the axes of joints O_i and O_j are determined by using the equations:

$$M_{rzi} = \vec{e}_i \cdot \vec{M}_{ri} = M_{ci} + \sum_{k=i}^{5} \vec{e}_i \cdot (\vec{F}_{uk} \times (\vec{r}_{tk} - \vec{r}_i)) + \sum_{k=i}^{5} \vec{e}_i \cdot \vec{M}_{uk} \tag{17}$$

$$M_{rzj} = \vec{e}_j \cdot \vec{M}_{rj} = M_{cj} + \sum_{k=j}^{5} \vec{e}_j \cdot (\vec{F}_{uk} \times (\vec{r}_{tk} - \vec{r}_j)) + \sum_{k=j}^{5} \vec{e}_j \cdot \vec{M}_{uk} \tag{18}$$

where M_{ci}, M_{cj} are the moments of drive mechanisms of the excavator manipulator in joints O_i and O_j.

The quantities of the moments of drive mechanisms of the excavator manipulator are determined by using the equations:

$$M_{ci} = sign(k_i) \cdot r_{ci} \cdot n_{ci} \cdot \left[\frac{d_{i1}^2 \pi}{4} p_{i1} - \frac{(d_{i1}^2 - d_{i2}^2)\pi}{4} p_{i2} \right] \cdot \eta_{cmi} \quad \forall \ \mathrm{i} = 3,4,5, \ \ \mathrm{k}_3 = 1, \ \ k_4 = k_5 = -1 \qquad (19)$$

where r_{ci} is the transfer function of the drive mechanism of the excavator manipulator [9], d_{i1}, d_{i2} are the diameters of the piston and connecting rod of the hydraulic cylinder, n_{ci} is the number of hydraulic cylinders in the mechanism, p_{i1}, p_{i2} are the measured pressures in the hydraulic cylinder on the piston side and on the connecting rod side of drive mechanism, η_{cmi} is the mechanical degree of the hydraulic cylinder efficiency.

The quantity of the lateral component of digging resistance W_z is determined by using the equation:

$$W_z = \left[\mathrm{r}_{c2} \cdot n_{c2} \cdot \frac{d_{c2} \cdot (p_{21} - p_{22})}{2\pi} \cdot \eta_{c2} + \sum_{k=2}^{5} \vec{e}_2 \cdot (\vec{F}_{uk} \times (r_{tk} - \vec{r}_2)) + \sum_{k=2}^{5} \vec{e}_2 \cdot \vec{M}_{uk} \right] \cdot \frac{1}{x_w} \qquad (20)$$

where r_{c2} is the transfer function of the drive mechanism of the excavator platform rotation, d_{c2} is the specific flow of the hydraulic motor of the platform rotation drive, n_{c2} – the number of rotating platform drives, p_{21}, p_{22} are measured pressures in the working ducts of the hydraulic motor, η_{c2} is the degree of efficacy of the excavator platform rotation drive.

The fictive interruption of the kinematic chain of the excavator in joint O_2 of rotating platform L_2 and the reduction of all loads, of the removed part, into its centre, yield:
the resulting force which subjects the slewing bearing to loading:

$$\vec{F}_2 = \vec{W} + \sum_{i=2}^{5} \vec{F}_{ui} \qquad (21)$$

and the resulting moment which subjects the slewing bearing to loading:

$$\vec{M}_2 = ((\vec{r}_w - \vec{r}_2) \times \vec{W}) + \sum_{i=2}^{5} ((\vec{r}_w - \vec{r}_2) \times \vec{F}_{ui}) + \sum_{i=2}^{5} \vec{M}_{ui} \qquad (22)$$

where $\vec{r}_2$ is the vector of the position of the joint centre (slewing bearing) O_2.

Components of force F_2 of joint O_2 along the coordinate axes:

$$\widehat{F}_{2x} = A_{o2} \vec{F}_2 \cdot \hat{\vec{i}}_2, \quad \widehat{F}_{2y} = A_{o2} \vec{F}_2 \cdot \hat{\vec{j}}_2, \quad \widehat{F}_{2z} = A_{o2} \vec{F}_2 \cdot \hat{\vec{k}}_2 \qquad (23)$$

Components of moment M_2 of joint O_2 along the coordinate axes:

$$\widehat{M}_{2x} = A_{o2} \vec{M}_2 \cdot \hat{\vec{i}}_2, \ \widehat{M}_{2y} = A_{o2} \vec{M}_2 \cdot \hat{\vec{j}}_2 \ \ \widehat{M}_{2z} = A_{o2} \vec{M}_2 \cdot \hat{\vec{k}}_2 \qquad (24)$$

where $A_{o2} = A_{2o}^T$ is transfer matrix from the absolute to local coordinate system $O_2 x_2 y_2 z_2$ [9].

Components of slewing bearing loads of the excavator rotating platform are axial force F_{2a}, radial force F_{2r}, and moment M_{2r}:

$$F_{2a} = \widehat{F}_{2y} \ ; \ \ F_{2r} = (\widehat{F}_{2x}^2 + \widehat{F}_{2z}^2)^{0,5} \ ; \ \ M_{2r} = (\widehat{M}_{2x}^2 + \widehat{M}_{2z}^2)^{0,5} \qquad (25)$$

The size of the bearing is selected on the basis of the determined equivalent spectrum of bearing loads and diagrams of bearing loading capacity, which are provided by the specialized bearing manufacturers.

The equivalent spectrum of bearing loads consists of an equivalent force and an equivalent bearing load moment determined by the equations for equivalent force F_e and equivalent moment M_e [10]:

$$F_e = (a \cdot F_{2a} + b \cdot F_{2r}) f_s \ ; \qquad M_e = f_s \cdot M_{2r} \tag{26}$$

where a is the factor of the axial force influence, b is the factor of the radial force influence, f_s is the factor of the bearing working conditions. Values of factors a,b,f_s are provided by the bearing manufacturers depending on the type of bearing (single-row, multi-row, ball, roller), type and size of machines and their working conditions.

3. PROGRAM

According to the previously defined mathematical model for determining the slewing bearing loads in a drive mechanism of an excavator rotating platform, it is necessary to measure the quantities of state (Table T1) (Fig. 1) of the excavator kinematic chain and drive mechanisms in operation under real-exploitation conditions.

A program (*EAOL*) is developed for computer processing and analyzing measured quantities. By employing measured quantities c_i,p_{i1},p_{i2} as input data, the program firstly determines, in the function of the duration of the work cycle, the geometric and kinematic quantities: generalized coordinates θ_i, coordinates of joint centers and mass centers of chain members, angular velocities $\dot{\theta}_i$ and angular accelerations $\ddot{\theta}_i$, and linear v_i and angular ω_i velocity and linear w_i and angular ε_i acceleration for the mass center of the excavator kinematic chain members.

Quantities of angular velocities and angular accelerations of the excavator kinematic chain members are determined on the basis of the double numerical differentiation by using the equations:

$$\dot{\theta}_i = \frac{\theta_{i(t+\Delta t)} - \theta_{i(t-\Delta t)}}{2\Delta t} \tag{27}$$

$$\ddot{\theta}_i = \frac{\theta_{i(t+2\Delta t)} - 2\theta_{i(t)} + \theta_{i(t-2\Delta t)}}{4\Delta t^2} \tag{28}$$

where: $\theta_{i(t)}$ is the generalized coordinate at moment t of the duration of the digging operation, $\theta_{i(t+\Delta t)}$, $\theta_{i(t-\Delta t)}$, $\theta_{i(t+2\Delta t)}$, $\theta_{i(t-2\Delta t)}$ are generalized coordinates (angles) in the moment of time which is larger or smaller for one or two intervals of time Δt than time t, Δt is the interval of time between two subsequent measurements of quantities.

The program further determines transfer functions r_{ci} and drive moments M_{ci} of individual drive mechanisms on the basis of the quantity parameters of actuators d_{i1},d_{i2} and measured pressures p_{i1},p_{i2} in their working ducts. Finally, after determining innate forces F_{ui} and moment M_{ui} of chain members, the program determines the vector of digging resistance W and components of force F_2 and moment M_2 of the bearing load.

4. EXAMPLE

As an example, the determination and analysis of the bearing loads are conducted on the basis of the results of the testing of a continuous tracks excavator BGH 600C, manufactured by IMK 14 October – Kruševac, with the mass of 16t and the power of 70 kW, equipped with an excavating manipulator with a bucket of 0,6 m^3 in capacity. Penetrometer measurements show that during the testing the excavation of category III and IV soil is performed [8]. Symbols, names and dimensions of measured quantities are given in Table 1, and the measuring chain is shown in Fig. 1c. The initial state of the measured quantities is defined on the horizontal contact surface of the support and movement mechanism, with the plane of the manipulator symmetry parallel to the transverse plane of the support and movement mechanism symmetry, with retracted hydraulic cylinder connecting rods and unloaded drive mechanisms. The sampling of measured quantities is conducted in the time interval Δt = 0,032 s. During the testing, forty-two full cycles are measured, from the digging operation, through the transfer and unloading of soil, to the operation of returning to the new beginning of excavation, with different manipulation tasks within the entire working range of the excavator.

Out of the total number of measurements, this paper separates and analyzes the measurements conducted during the digging of a canal, equal in width to the bucket, from the excavator support surface. For the spatial orientation of the measured quantities and obtained results of the analyzed cycle, a path of the center of the bucket cutting edge is given (Fig. 1) in *OXY* and *OXZ* plane of the absolute coordinate system. Part of the obtained results is presented in the diagrams of measured (Fig. 2) and determined quantities (Fig. 3) in the function of the duration of the excavator work cycle. Out of the measured quantities the diagrams show changes in: the movement of the support and movement mechanism c_1 (Fig. 2a), the angle of platform rotation $\square_2$ and the motions of hydraulic cylinders c_3, c_4, c_5, and pressures p_{i1},p_{i2} (Fig. 2b, c) in the ducts of the excavator drive mechanism actuators. Diagrams of drive mechanism actuator motion (Fig. 2a) show that the selected manipulation testing task is conducted with the simultaneous movement of at least two members of the excavator kinematic chain. Depending on the position, the digging process is performed with a separate or simultaneous movement of the manipulator bucket and stick. At the beginning and the end of the digging process the lifting (movement) of the support and movement member occur, while the angle of platform rotation is relatively small. The operation of material transfer from the plane of digging into the plane of unloading is performed by a simultaneous raising of the boom and platform rotation. The operation of material unloading is performed by moving the bucket and stick, and the operation of returning to the plane of digging by moving the boom and stick with platform rotation. During the digging operation, a gradual increase in pressures occurred in the working chambers of the actuators up to their maximal values (Fig. 2b, c). Due to the discontinuation of the digging process, drastic changes appear in pressures in the drive mechanism actuators. Abrupt changes in pressures in the hydraulic motor ducts of the platform rotation drive take place when the platform start and stop moving during the operation of material transfer.

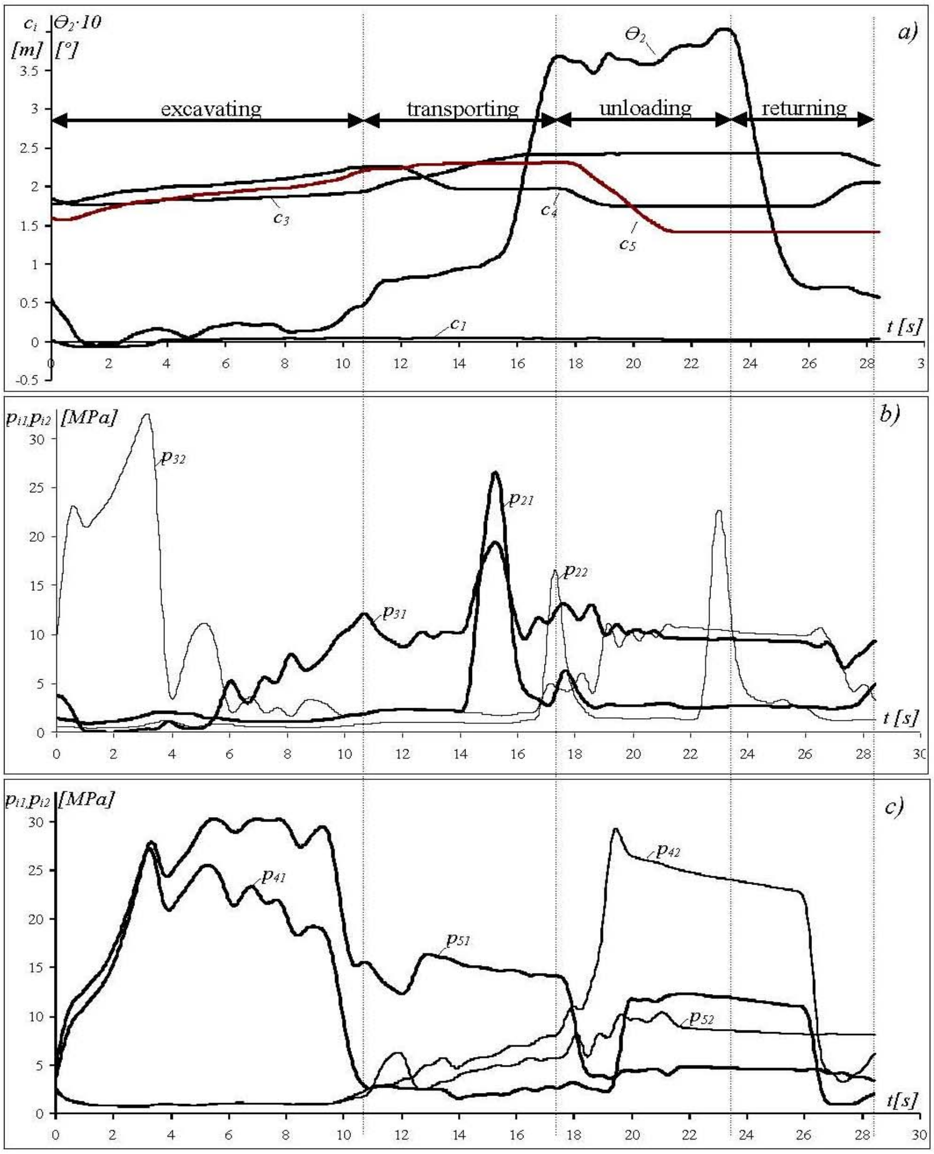

Fig. 2 Measured quantities of the state of the excavator: a) movement of the rotating mechanism, angle of the platform rotation and motions of manipulator hydraulic cylinders, b, c) pressures in the excavator drive mechanism actuators

Out of the determined quantities, obtained by using the developed program, the paper shows the change in the quantities of platform drive mechanism during the cycle, based on the components of force F_2 and moment M_2 (Fig. 3a, b) of the bearing loads in the static and dynamic mathematical model of the excavator. As the diagrams show, bearing loads determined by using the static and dynamic mathematical model of the excavator

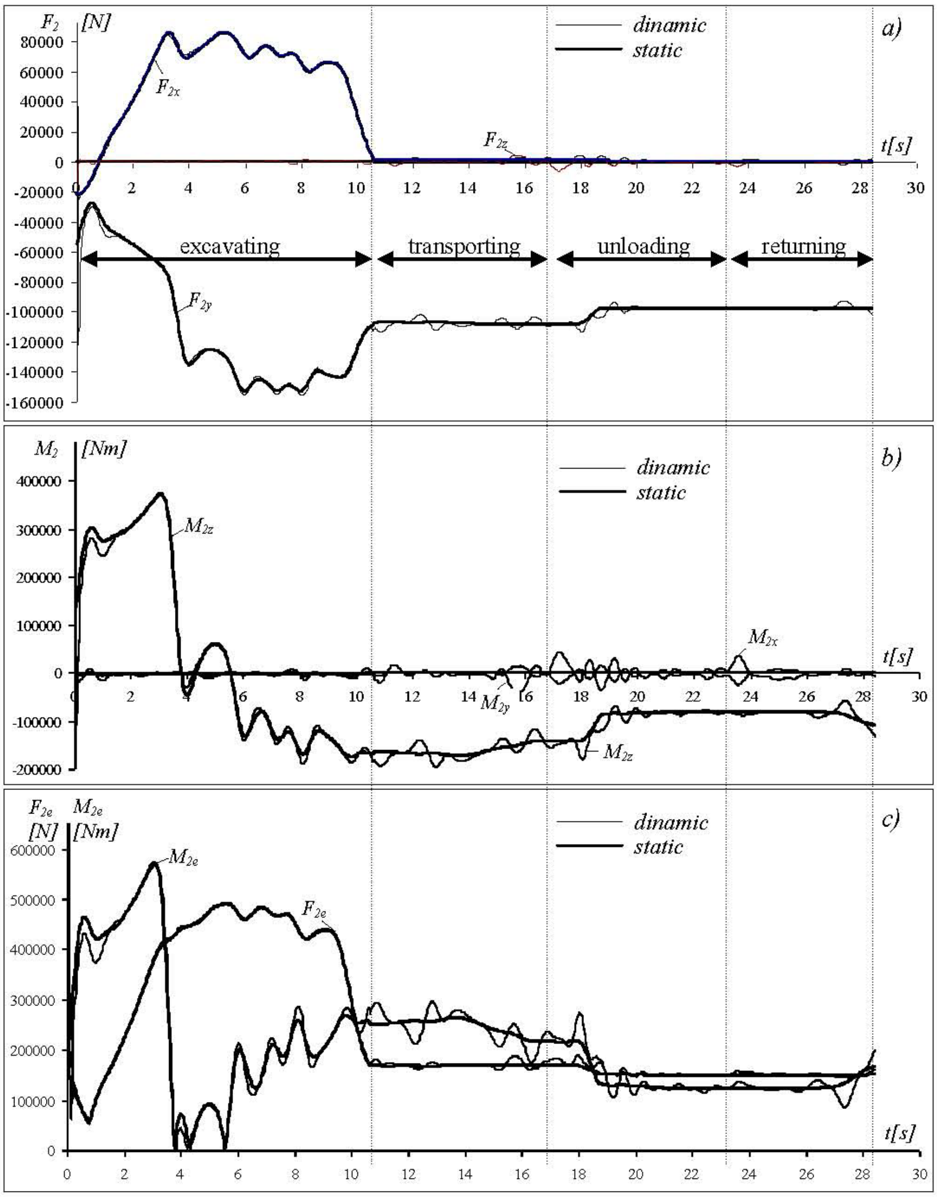

Fig. 3 Loading of the platform rotation drive bearing: a) bearing load force components, b) bearing load moment components, c) equivalent bearing load force and moment.

vary only slightly during the major part of the digging process, which shows that the dynamic influence due to the movement of the excavator kinematic chain members during the digging process is small since the digging process itself takes place relatively slowly. The dynamic influence on the loading of the bearing occurs at the beginning and the end of the digging process when the lifting (movement) of the support and movement member takes place as well, which also causes the appearance of increased dynamic forces and moments in all members of the excavator kinematic chain. The increased dynamic loadings of the bearing occur at the beginning and the end of the operation of soil transfer and returning to the new plane of digging due to the movement of the excavator platform when the masses of the manipulator kinematic chain members, carried by the excavator rotating platform, accelerate and decelerate.

Dynamic changes in the loading of the bearing also occur during the unloading operation due to the abrupt change in the dynamic parameters by reducing the mass of soil when the bucket is emptied.

During the work cycle of the excavator, the greatest values of the components of force (Fig. 3a) and moment (Fig. 3b) of the slewing bearing loads, as well as the greatest values of the equivalent force and the equivalent moment of bearing loads, applicable for the selection of the bearing size, occur during the digging operation.

5. CONCLUSION

The conducted research, whose part is presented in this paper, represent a contribution to the analysis of defining the character of change in the bearing loads in the rotating platform drive mechanism of hydraulic excavators during the digging process with an excavating manipulator. The analysis shows that the greatest loads, applicable for the adequate bearing selection, according to the criteria of global bearing manufacturers, occur during the digging operation. The importance of knowledge of bearing load vectors is the basis of necessary mechanical, energy and structural simulations and analyses with the aim of optimizing the structure and drive mechanisms of the excavator.

The developed software and the set of measured quantities obtained during the conducted testing of the hydraulic excavator can be used not only to define the bearing load vectors but also for other dynamic analyses of the excavator.

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EKSPERIMENTALNO ODREĐIVANJE OPTEREĆENJA LEŽAJA POGONA OBRTNE PLATFORME HIDRAULIČKIH BAGERA

U radu je dat postupak za eksperimentalno određivanje opterećenja aksijalnog ležaja pogonskog mehanizma obrtne platforme hidrauličkih bagera sa dubinskim manipulatorom. Definisan je matematički model koji omogućuje da se, na osnovu merenih veličina stanja bagera pri radu u ekploatacionim uslovima, posredo, odrede vektori sile i momenta opterećenja ležaja. Pri čemu se merene veličine stanja bagera odnose na položaj kinematičkog lanca i pritiske hidrostatičkog sistema u vodovima aktuatora pogonskih mehanizama bagera. Kao primer, dati su rezultati istraživanja dobijeni pri ersperimentalnom određivanju opterećenja aksijalnog ležaja pogona okretanja obrtne platforme hidrauličkog bagera mase 16000 kg.

Ključne reči: *hidraulički bageri, opterećenja ležaja obrtne platforme*