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[1.] Vesna JOVANOVIĆ, [2.] Dragoslav JANOŠEVIĆ, [3.] Jovan PAVLOVIĆ

EXPERIMENTAL ANALYSIS OF MANIPULATOR JOINTS LOADING IN HYDRAULIC EXCAVATORS

[1,2,3.] University of Niš, Faculty of Mechanical Engineering, A. Medvedeva 14, SERBIA

Abstract: The paper provides a procedure for experimental determination of loading to which elements of kinematic pairs (joints) of the kinematic chain and drive mechanisms in an excavating manipulator of hydraulic excavators with continuous tracks are subjected. A mathematical model is defined to enable the determination of force and moment vectors of joints loading, on the basis of the measured quantities of the excavator state during the operation in exploitation conditions. The measured quantities of the excavator state relate to the position of the kinematic chain and the pressures of the hydraulic system in the ducts of the excavator drive mechanisms actuators. As an example, the paper provides research results obtained during experimental determination of loading of kinematic pairs (joints) in a hydraulic excavator of 17,000 kg in mass.
Keywords: hydraulic excavators, manipulator joints loading

1. INTRODUCTION

The primary function of hydraulic excavators, of all sizes, is the cyclic transport of various materials in the variable working range. It is characteristic that operating cycles of hydraulic excavators consist in repeating 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 structural support of the excavator operating cycle is the kinematic chain of the general configuration comprising the support and movement mechanism, the rotating platform and the multi-member manipulator which can be equipped with various tools for performing different functions. Members of the manipulator kinematic chain form kinematic pairs connected by fifth-class rotary joints. Drive mechanisms of kinematic chain members in an excavator manipulator are constructed using hydraulic actuators: hydraulic motors or two-way hydraulic cylinders.

The research conducted in this area relate to: a) analytical modelling and experimental determination of load during the digging process [1][2], b) development of mathematical models for kinematic and dynamic excavator analysis [3][4], c) development of drive mechanisms and control systems [5-7], and d) definition of indicators for analysis and evaluation of excavator digging efficiency [8].

The aim of the paper is to analyse the loading to which members and joints of the kinematic chain of an excavator manipulator are subjected during the operating cycle of the machine, so as to determine the size and character of changes in loading that are relevant for their reliable dimensioning.

2. MATHEMATICAL MODEL

In this paper a mathematical model is developed to determine the loading of kinematic pairs (joints) and members of the excavating manipulator in hydraulic excavators, based on the measured quantities of the state of the kinematic chain and drive mechanisms of the excavator Table 1, Figure 1, during the operation of the machine in exploitation conditions.

The mathematical model encompasses the general five-member configuration of the excavator which comprises: the support and movement member L_1 Figure 1a, the rotating platform L_2, and the three-member planar manipulator with: the boom L_3, stick L_4 and tool L_5 in the form of a digging bucket with a specific capacity.

The members of the kinematic chain of the excavator form fifth-class pairs – rotary joints with a single degree of freedom. Axes of joints 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 form a third-class zero joint with potential movements in the plane of the surface. The kinematic chain of the manipulator considered in the excavator model is of planar configuration. The exes of joints are parallel, while the centres of the manipulator joints O_i (i=3,4,5) 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 centre of the bucket cutting edge O_w. Elements of fifth-class rotary joints of drive mechanisms of the excavator manipulator are derived in the form of a single pair of sliding shells 1 Figure 1b, embedded in the hub of the relatively mobile member L_i and the clevis pin 2 linked to the relatively immobile member L_{i-1} of the kinematic pair. Basic dimensions of the joint are: the diameter of the clevis pin (shaft) d_{si}, the width of the sliding shell b_{si}, the diameter of the hub D_{si}, the span of the shells l_{si}, and the span of the hub L_{si}.

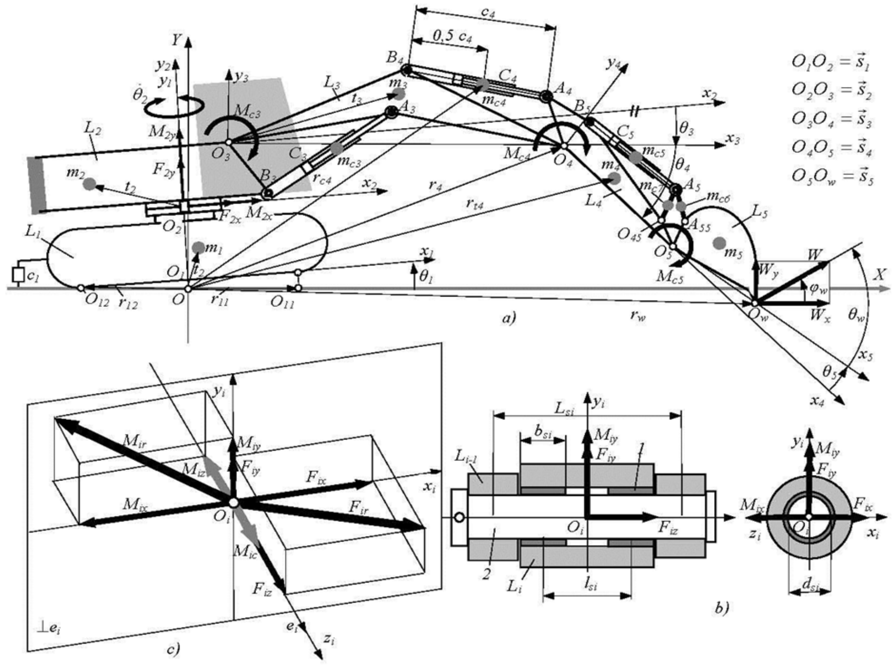

Figure 1. Hydraulic excavator model: a) kinematic chain, b) elements of kinematic pairs (joints), c) components of loading force and moment in joints

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

- the support surface and kinematic chain members are modelled 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 (longitudinal x-x or transverse z-z) Figure 1a, excavator rollover lines,
- during the manipulation task, the kinematic chain of the excavator is subjected to gravitational, innate and external (technological) forces – digging resistances W,
- the position of the mass centre of a hydraulic cylinder is in the middle of the current length of that hydraulic cylinder,
- friction resistances are neglected in the joints of the kinematic chain and drive mechanisms of the excavator.

The area of the excavator model is determined by an absolute coordinate system OXYZ Figure. 1a with unit vectors i, j, k along the coordinate axes. The excavator support surface lies in the horizontal OXZ plane of the absolute coordinate system, while the vertical OY axis of the same system falls on the axis of the support member-rotation member kinematic pair when the excavator is positioned on the horizontal surface.

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

$$L_i = \left\{ \hat{e}_i, \hat{s}_i, \hat{t}_i, m_i, \hat{J}_i \right\} \tag{1}$$

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

Vector quantities marked with caps relate to the local coordinate system, while those without caps relate to the absolute coordinate system.

The internal (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 the previous member L_{i-1} upon rotation around the joint O_i axis. The lifting angle of the 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 the manipulator member L_i in relation to the previous member L_{i-1} are determined depending on the measured length c_i of the hydraulic cylinders of the manipulator boom, stick and bucket drive mechanisms.

Unit vector e_i of joint O_i axis of the excavator kinematic pair in the absolute coordinate system is determined using the equation:

$$e_i = A_{io}\widehat{e}_i \tag{2}$$

Unit vector e_1 of the first joint axis is directed along the potential (longitudinal x-x or transverse z-z) Figure 1a, excavator rollover lines.

Vector r_i of joint O_i centre of the excavator kinematic pair in the absolute coordinate system is determined using the equation:

$$r_i = \sum_{j=1}^{i-1} A_{jo}\widehat{s}_j \quad \forall\ i=2,3,4,5 \tag{3}$$

Vector r_w of the centre of the bucket cutting edge in the absolute coordinate system is determined using the equation:

$$r_w = \sum_{i=1}^{5} A_{io}\widehat{s}_i \tag{4}$$

Vectors r_{ti} of the centre of the excavator kinematic chain member L_i mass in the absolute coordinate system are determined using the equation:

$$r_{ti} = r_i + A_{io}\widehat{t}_i \tag{5}$$

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

Kinematic quantities for the centre of the 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 the previous member L_{i-1} is taken as transferable, while the movement of the observed member L_i in joint O_i is taken as relative.

To determine the kinematic quantities of the chain member L_i in relation to the absolute coordinate system, recursive equations are used [9]:

$$\omega_i = \omega_{i-1} + \dot{\theta}_i e_i \tag{6}$$

$$\varepsilon_i = \varepsilon_{i-1} + \ddot{\theta}_i e_i + \left(\omega_{i-1} \times \dot{\theta}_i e_i\right) \tag{7}$$

$$v_i = v_{i-1} + \left(\omega_{i-1} \times \left(s_{i-1} - t_{i-1}\right)\right) + \left(\omega_i \times t_i\right) \tag{8}$$

$$w_i = w_{i-1} + \left(\varepsilon_{i-1} \times \left(s_{i-1} - t_{i-1}\right)\right) + \omega_{i-1} \times \left(\omega_{i-1} \times \left(s_{i-1} - t_{i-1}\right)\right) + \left(\varepsilon_i \times t_i\right) + \omega_i \times \left(\omega_i \times t_i\right) \tag{9}$$

where: $\dot{\theta}_i, \ddot{\theta}_i$ – the angular velocity and angular acceleration 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:

$$F_i = -m_i w_i \tag{10}$$

the moment of innate forces M_{iu}, which is determined on the basis of Euler's dynamic equations:

$$\widehat{M}_{iu} = -\widehat{J}_i \widehat{\varepsilon}_i + \left(\widehat{\omega}_i \times \widehat{J}_i \widehat{\omega}_i\right);\ M_{iu} = A_{io}\widehat{M}_{iu} \tag{11}$$

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

$$F_{iu} = F_i - m_i g\, j \tag{12}$$

Bearing in mind the assumption that the vector of digging resistance W acts in the centre 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=2,3,4,5) can set the equilibrium conditions, for the removed chain parts, which can used to determine the vector of resistance W on the basis of the measured quantities of the excavator state during the operation in exploitation conditions [10].

Force F_{ir} Figure 1c and moment M_{ir} of the loading of the elements of joint O_i, Figure 1b, are determined by using the fictive interruption in the manipulator kinematic chain in the same joint, and by reducing all of the loads of the given part of the chain to the centre of the joint (j>i) using the equations:

$$F_{ir} = F_{ic} + W + \sum_{j=i}^{5} F_{ju} \quad \forall\ i=3,4,5 \tag{13}$$

$$M_{ir} = M_{ic} + \left(r_w - r_i\right) \times W + \sum_{j=i}^{5} M_{ju} + \sum_{j=i}^{5} \left(r_{tj} - r_i\right) \times F_{ju} \quad \forall\ i=3,4,5 \tag{14}$$

where: F_{ic} – the force in the hydraulic cylinder of the drive mechanism, M_{ic} – the moment of the drive mechanism, W – the potential digging resistance.

The force F_{ic} and moment M_{ic} quantities of drive mechanisms of the excavator manipulator are determined using the equations:

$$F_{ic} = n_{ic} \cdot \left[\frac{d_{i1}^2 \pi}{4} p_{i1} - \frac{\left(d_{i1}^2 - d_{i2}^2\right)\pi}{4} p_{i2} \right] \cdot \eta_{cmi} \qquad \forall i = 3,4,5 \tag{15}$$

$$M_{ic} = \text{sign}(k_i) \cdot r_{ic} \cdot F_{ic} \qquad \forall i = 3,4,5, \; k_3 = 1, \; k_4 = k_5 = -1 \tag{16}$$

where: n_{ic} – the number of hydraulic cylinders in the drive mechanism, p_{i1}, p_{i2} – the measured pressure in the hydraulic cylinder on the piston side and on the connecting rod side of the drive mechanism, η_{cmi} – the mechanical degree of efficiency of the hydraulic cylinder, r_{ic} – the transmission function of the drive mechanism of the excavator manipulator [9].

Components of force F_{ir} and moment M_{ir} of the loading of joint O_i of the excavator kinematic chain in the local coordinate system of member L_i:

$$\widehat{F}_{ix} = A_{oi} F_{ir} \cdot \widehat{i}, \quad \widehat{F}_{iy} = A_{oi} F_{ir} \cdot \widehat{j}_i, \quad \widehat{F}_{iz} = A_{oi} F_{ir} \cdot \widehat{k}_i, \quad i = 3,4,5 \tag{17}$$

$$\widehat{M}_{ix} = A_{oi} M_{ir} \cdot \widehat{i}, \quad \widehat{M}_{iy} = A_{oi} M_{ir} \cdot \widehat{j}_i, \quad \widehat{M}_{iz} = A_{oi} M_{ir} \cdot \widehat{k}_i, \quad i = 3,4,5 \tag{18}$$

where: A_{oi} – the transfer matrix used to transfer the vector quantities from the absolute coordinate system OXYZ to the local coordinate system $O_i x_i y_i z_i$ of member L_i. During the manipulation task, the drive moment of mechanism M_{ic} overcomes the components of loading moments which are collinear with the joint $e_i = \widehat{k}_i$ axis, thus the resulting moment for the joint O_i axis is equal to $\widehat{M}_{iz} = 0$, while the other components of joint loads strain the joint structure, and some even cause friction between its elements.

3. PROGRAM

According to the previously defined mathematical model for determining the loading of kinematic pairs (joints) of the manipulator, it is necessary to measure the quantities of state Table T1, Figure 1, of the excavator kinematic chain and drive mechanisms in operation under real-exploitation conditions.

A program is developed to process and analyze the measured quantities using a computer. By employing the measured quantities c_i, p_{i1}, p_{i2} as input data, the program first determines, in the function of the duration of the operating cycle, the geometric and kinematic quantities: generalized coordinates θ_i, coordinates of joint centres and mass centres 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 centre of the excavator kinematic chain members.

Table1. Measured quantities of the state of the excavator kinematic chain and drive mechanisms

Measuring spot	Name of the measured quantity	Symbol	Dimension
M1	Lifting of the support and movement mechanism	c_1	m
M2	Platform rotation angle	c_2	°
M3	Boom hydraulic cylinder motion	c_3	m
M4	Stick hydraulic cylinder motion	c_4	m
M5	Bucket hydraulic cylinder motion	c_5	m
M6	Pressure in one duct of the hydraulic motor for platform rotation drive	p_{21}	MPa
M7	Pressure in the other duct of the hydraulic motor for platform rotation drive	p_{22}	MPa
M8	Pressure in the boom hydraulic cylinder on the piston side	p_{31}	MPa
M9	Pressure in the boom hydraulic cylinder on the connecting rod side	p_{32}	MPa
M10	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 hydraulic cylinder on the connecting rod side	p_{52}	MPa

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

$$\dot{\theta}_i = \frac{\theta_{i(t+\Delta t)} - \theta_{i(t-\Delta t)}}{2\Delta t} \tag{19}$$

$$\ddot{\theta}_i = \frac{\theta_{i(t+2\Delta t)} - 2\theta_{i(t)} + \theta_{i(t-2\Delta t)}}{4\Delta t^2} \tag{20}$$

where: $\theta_{i(t)}$ – the generalized coordinate in the moment t of the duration of the digging operation, $\theta_{i(t+\Delta t)}$, $\theta_{i(t-\Delta t)}$, $\theta_{i(t+2\Delta t)}$, $\theta_{i(t-2\Delta t)}$ – the 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 – the interval of time between the two subsequent measurements of quantities.

The program further determines the 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 the innate forces F_{ui} and moment M_{ui} of chain members, the program determines the vector of digging resistance W and components of forces F_i and moments M_i of the loading of joints O_i (i=3,4,5) of the kinematic chain of the excavator manipulator.

As an example, the determination and analysis of the loading of the kinematic chain joints was performed on the basis of the testing results of an excavator with continuous tracks, of 17,000 kg in mass and 70 kW in power, equipped with an excavating bucket of 0.6 m^3 in volume. The sampling of measured quantities was conducted in the time interval Δt=0,032 s. During the testing, forty-two full cycles were measured with different manipulation tasks within the entire working range of the excavator.

Out of the total number of measurements, here separated and analysed are the measurements conducted during the digging cycle of a canal with the maximum depth of around 1.2 m and equal in width to the bucket, which corresponds to the measured quantities given in the diagrams that show the change in: the movement of the support and movement mechanism c_1 Figure 2a, the angle of platform rotation Θ_2, and the motion of hydraulic cylinders c_3,c_4,c_5, and pressures p_{i1},p_{i2} Figure 2b,c (i=2,..,5) in the ducts of the excavator drive mechanisms actuators.

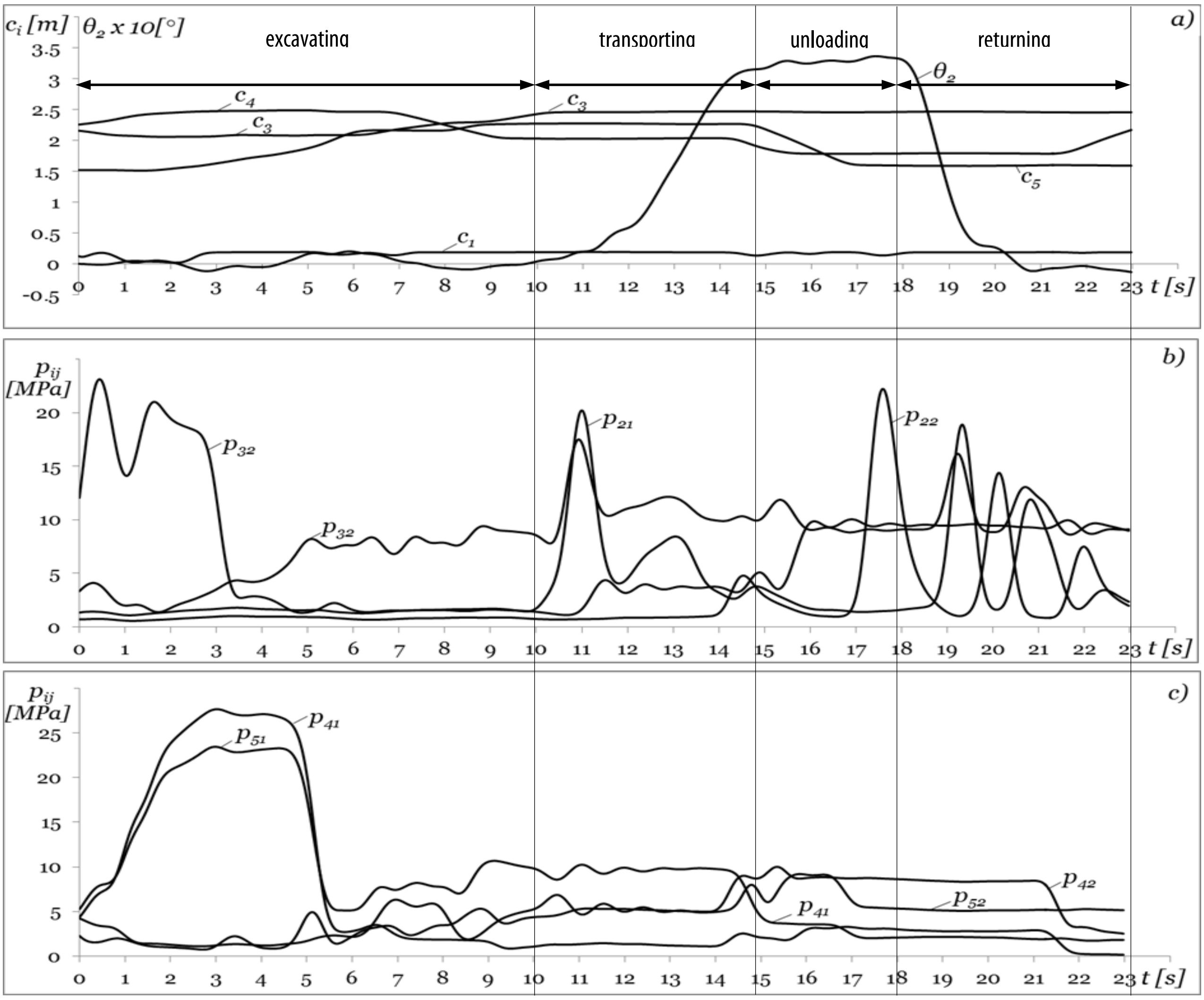

Figure 2. Measured quantities of the excavator state: a) movement of the movement mechanism c_1, angle of the platform movement θ_2 and motions of hydraulic cylinders c_3,c_4,c_5 of the manipulator, b, c) pressures p_{i1},p_{i2} in excavator drive mechanisms actuators

Out of the determined quantities, obtained by using the developed program, the paper shows the change in the quantities of the components of force Figure 3a,4a,5a, and moment Figure 3b,4b,5b, of the loading of joints O_3, O_4 and O_5 of the kinematic chain of the manipulator during the operating cycle of the excavator.

The diagram of the resulting force $\widehat{F}_3$ Figure 3a, in joint O_3 of the kinematic chain of the excavator manipulator, and its components $\widehat{F}_{3x}$, $\widehat{F}_{3y}$, $\widehat{F}_{3z}$ shows that the resulting force and its components have the highest value during the material transport operation, when the boom lifts simultaneously with the rotation of the platform with a full bucket of the material. It is characteristic that components $\widehat{F}_{3x}$ and $\widehat{F}_{3y}$ have an alternating loading character during the excavation operation and the operation of returning to the new digging position. Component $\widehat{F}_{3z}$ is significantly smaller than the other components and its alternating value occurs at the beginning of the platform rotation towards the plane of unloading and at the beginning of the platform rotation towards the new plane of excavation.

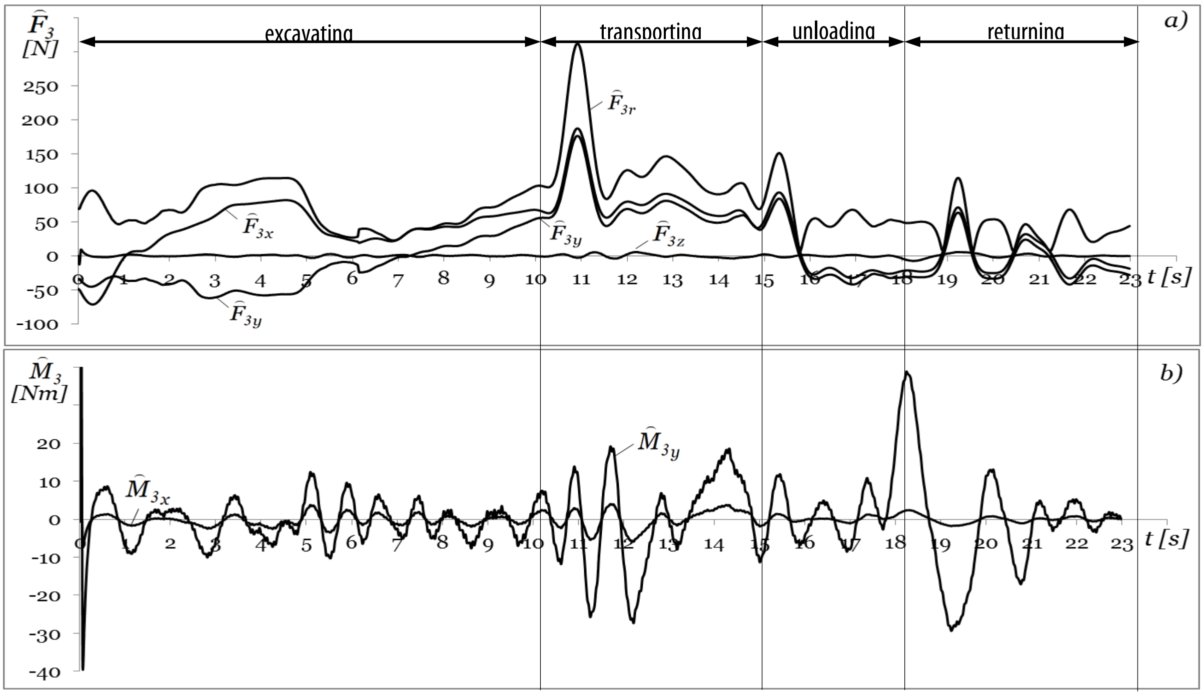

Figure 3. Loading of the kinematic pair (joint) O_3 of the kinematic chain of the excavating manipulator in hydraulic excavators: a) components of loading forces of the joint, b) components of loading moments of the joint

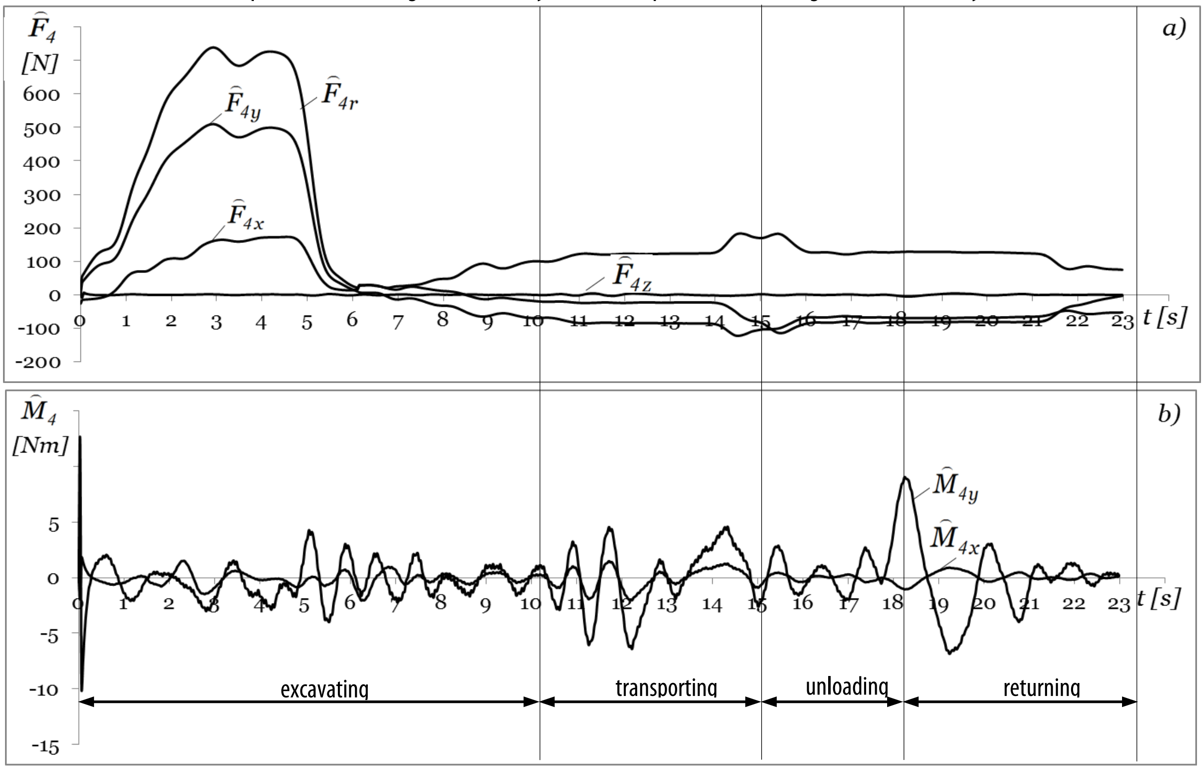

Figure 4. Loading of the kinematic pair (joint) O_4 of the kinematic chain of the excavating manipulator in hydraulic excavators: a) components of loading forces of the joint, b) components of loading moments of the joint

Also, component $\widehat{M}_{3y}$ Figure 3b, of the moment of the loading of joint O_3 has the most prominent oscillatory changes at the beginning of the platform rotation towards the plane of unloading and at the beginning of the platform rotation towards the new plane of excavation with an empty bucket, where it reaches the maximum value. Component $\widehat{M}_{3x}$ of the loading of joint has a smaller value with a characteristic change in the loading when the full bucket exits the pit (canal) and at the beginning of the material transport.

The diagram of the resulting force $\widehat{F}_4$ Figure 4a, in joint O_4 of the kinematic chain of the excavator manipulator, and its components $\widehat{F}_{4x}$, $\widehat{F}_{4y}$, $\widehat{F}_{4z}$ shows that the resulting force and its components have the highest value during the excavation operation. Component $\widehat{F}_{4z}$ is negligible in comparison to components $\widehat{F}_{4x}$, $\widehat{F}_{4y}$ which act in one direction during the excavation operation, and then in the opposite direction after the excavation operation.

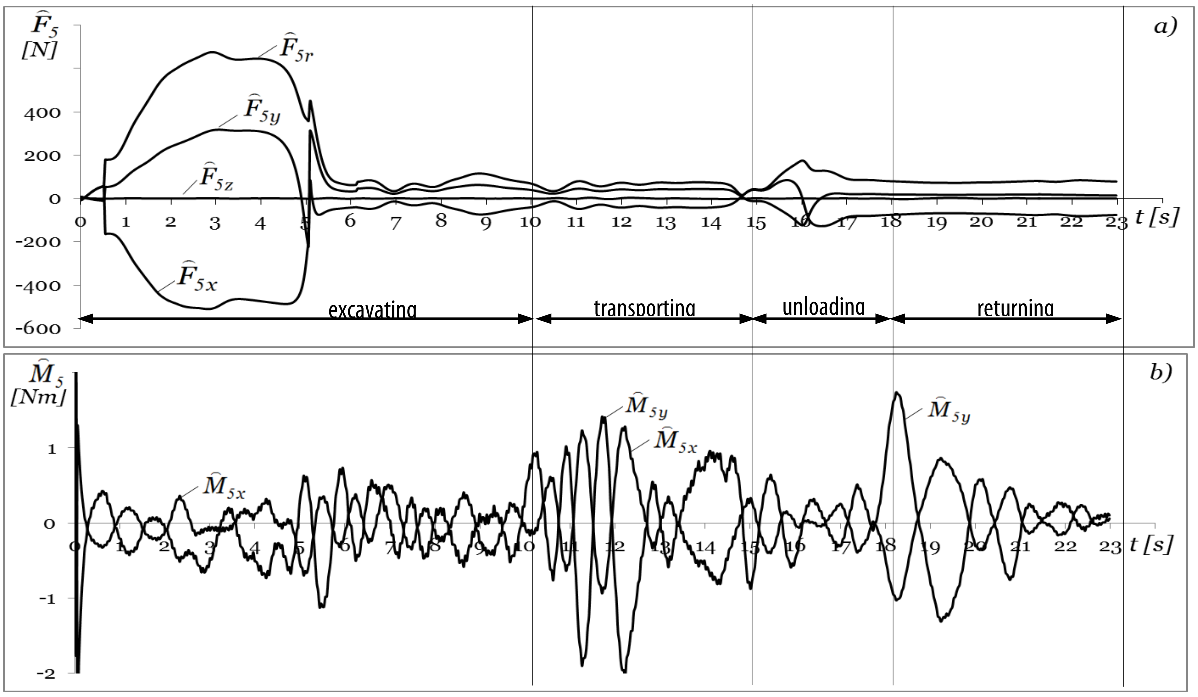

Figure 5. Loading of the kinematic pair (joint) O_5 of the kinematic chain of the excavating manipulator in hydraulic excavators: a) components of loading forces of the joint, b) components of loading moments of the joint

Component $\widehat{M}_{4y}$ Figure 4b, of the moment of loading has the highest value at the beginning of the platform rotation towards the new plane of excavation with an empty bucket, and it is significantly larger than component $\widehat{M}_{4x}$ of the moment of loading which has an alternating loading character of small magnitude. The diagram of the resulting force $\widehat{F}_5$ Figure 5a, in joint O_5 of the kinematic chain of the excavator manipulator, and its components $\widehat{F}_{5x}$, $\widehat{F}_{5y}$, $\widehat{F}_{5z}$ shows that the resulting force and its components have the highest value during the excavation operation. Components $\widehat{F}_{5x}$, $\widehat{F}_{5y}$ act in opposite directions during the excavation operation and are of significantly larger magnitude in comparison to component $\widehat{F}_{5z}$.

Characteristic small magnitude changes in forces of joint O_5 occur during the material unloading operation. The change in magnitude of moment components $\widehat{M}_{5x}$, $\widehat{M}_{5y}$ of the loading of joint O_5 Figure 5b, occurs during the transport of the material, the rotation of the platform, and at the very beginning of the operation of returning the empty bucket to the new plane of excavation.

The comparative analysis of the loading of kinematic chain joints in a hydraulic excavator shows that the maximal forces do not occur during the same cycle operations, however, the magnitude of the forces in joints O_4 and O_5 is almost twice the size of the magnitude in joint O_3. On the other hand, the maximal values of the loading moment of joints occur during the same cycle operations, but the magnitude, for example, of the moments in joint O_3 is ten times greater than the moments of the loading of joint O_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 loading of kinematic pairs (joints) of the kinematic chain of an excavating manipulator in hydraulic excavators. Research results show that the elements of kinematic pairs (joints) of the kinematic chain of an excavating manipulator are subjected to the alternating influence of forces and moments. The importance of knowledge of joint loading vectors is the basis of necessary structural analyses with the aim of optimization, reliability and life cycle of the structure of the kinematic chain members of the manipulator 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 joint loading vectors but also for other dynamic analyses of the excavator.

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REFERENCES

[1.] Maciejewski, J., Jarzebowski, A., Trampczynski, W.: Study on the efficiency of the digging process using the model of excavator bucket, Journal of Terramechanics, Vol. 40, pp. 221-233 (2004).
[2.] Milčić D., Miladinović S., Mijajlović M., Marković B. :Determination of the of Bucket Wheel Excavator SRs 1300 Load Spectrum in the Coal Strip Mine Drmno, FAMENA, Vol. 37, No 1, pp. 77-88 (2013).
[3.] Bhaveshkumar P. P., PRAJAPATI J.: Review on kinematics of hydraulic excavator's backhoe attachment, International Journal of Engineering Science and Technology (IJEST), Vol. 3 No. 3, pp.1990-1997 (2011).
[4.] Hall, A.S., McAree, P.R.: Robust bucket position tracking for a large hydraulic excavator, Mechanism and Machine Theory, Vol 40, pp. 1-16 (2005).
[5.] Plonecki, L., Trampczynski, W., Cendrowicz J.: A concept of digital control system to assist the operator of hydraulic excavators, Automation in Construction, Vol. 7, pp. 401–411 (1998).
[6.] Chang, P. H., Soo-Jin Lee: A straight-line motion tracking control of hydraulic excavator system, Mechatronics, Vol.12, pp. 119-123 (2002).
[7.] Geu Flores, F., Kecskemethy, A., Pottker A. :Workspace Analysis and Maximal Force Calculation of a Face-Shovel Excavator using Kinematical Transformers, 12th IFToMM World Congress, Besancon, pp. 18-21 (2007).
[8.] Sung-Uk L. Chang P. H.: Control of a heavy-duty robotic excavator using time delay control with integral sliding surface, Control Engineering Practice, Vol. 10, pp.697-711 (2002).
[9.] Janošević D.: Optimal Synthesis of Drive Mechanisms in Hydraulic Excavators, doctoral dissertation, Faculty of Mechanical Engineering, University of Niš, 1997.
[10.] Jovanović V., Janošević D.,Pavlović J.: Experimental determination of resistance digging of hydraulic excavator, IMK-14 – Research & Developement in Heavy Machinery, Vol. 19, No. 3, pp.83-88 (2013)

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