Eksperimentalna analiza parametara pogonskog mehanizma obrtne platforme hidrauličnih bagera

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U ovom radu predstavljen je metod za eksperimentalno određivanje parametara pogonskog mehanizma obrtne platforme hidrauličnih bagera sa dubinskim manipulatorom. Definisan je matematički model kojim se određuju kinematički i dinamički parametri pogonskog mehanizma obrtne platforme hidrauličnih bagera, na osnovu merenih veličina stanja rada bagera u eksploatacionim uslovima. Dobijeni eksperimentalni rezultati pokazuju da su najveća opterećenja aksijalnog ležaja pogona okretanja platforme pri operaciji kopanja. Osim toga izrazite dinamičke promene parametara hidrostatičkog sistema pogonskog mehanizma obrtne platforme javljaju se pri operaciji prenosa materijala.

Ključne reči: hidraulički bageri, obrtna platforma, ispitivanje

1. UVOD

Neophodnu prostornu manipulaciju hidrauličkim bagerima omogućuje prvi kinematički par opšte konfiguracija kinematičkog lanca mašine koji grade: oslonno-kretni mehanizam i obrtna platforma povezani obrtnim zglobovom pete klase u obliku aksijalnog ležaja. Oslonjen na podlogu oslonno-kretni mehanizam je pri tome relativno nepomični član u odnosu na obrtnu platformu koja može da ostvari obrtanje u oba smera oko vertikalne ose zgloba.

Opšti model pogonskog mehanizma obrtne platforme bagera čine: hidromotor 5 (sl.1), reduktor 6 sa zupčanicom 6.1 na izlaznom vratilu i aksijalni ležaj 7 sa ozubljenim unutrašnjim 7.1 i neizubljenim spoljašnjim 7.2 prstenom. Hidromotor pogona napaja dvostrujna hidropumpa 3.1 pogonjena dizel motorom 1. Regulacijom hidropumpe pomoću upravljačkog razvodnika 4.1 postiže se promena smera okretanje platforme.

Sinteza kompletnog pogona obrtnih platformi hidrauličnih bagera obuhvata:

a) izbor konceptijskog rešenja pogona, b) izbor aksijalnog ležaja na osnovu detaljne analize opterećenja ležaja u celom radnom području mašine, c) izbor hidromotora, reduktora i hidropumpe pogona okretanja, d) analiza elemenata zavrtnjske veze i noseće strukture za koju se ležaj vezuje.

Za optimalnu sintezu pogona okretanja platforme neophodno je poznavanje kinematičkih i dinamičkih parametara pogona.

2. MATEMATIČKI MODEL

U ovom radu prikazan je metod za eksperimentalnu analizu kinematičkih i dinamičkih parametara pogona platforme bagera, na osnovu merenih veličina stanja rada bagera u eksploatacionim uslovima.

Metod eksperimentalne analize pogona platforme zasnovan je na razvijenom dinamičkom matematičkom modelu bagera sa petočlanom konfiguracijom kinematičkog lanca sastavljenom od: oslonno-kretnog člana L_1 (sl.2), obrtnog člana (obrtne platforme) L_2 i tročlanog ravanskog manipulatora sa: strelom L_3 , rukom L_4 i kašikom L_5 .

Matematičkim modelom bagera obuhvaćen je skup veličina (sl. 2.) [1][2] :

- parametara članova kinematičkog lanca bagera

$$L_i = \{e_i, s_i, t_i, m_i, J_i\} \quad \forall i = 1, \dots, 5 \quad (1)$$

- parametara pogonskih mehanizama bagera:

$$C_i = \{d_i, a_i, b_i, m_{ci}\} \quad \forall i = 1, \dots, 5 \quad (2)$$

gde je: e_i - jedinični vektor ose zgloba O_i kojim se član L_i vezuje za prethodni član L_{i-1} , s_i - vektor položaja središta zgloba O_{i+1} kojim se član lanca L_i vezuje za naredni član L_{i+1} , t_i - vektor položaja središta mase člana, m_i - masa člana, J_i - moment inercije člana, d_i - parametri veličina aktuatora (hidromotora i hidrocilindara) pogonskih mehanizama; a_i , b_i - vektori položaja zglobova u kojima se aktuatori vezuju za kinematički lanac bagera, m_{ci} - masa pogonskog mehanizma.

Slika 1. Pogonski mehanizam obrtne platforme hidrauličnih bagera

Slika 2. Matematički model bagera za eksperimentalno ispitivanje parametara pogonskog mehanizma obrtne platforme

Merene veličine stanja kinematičkog lanca bagera su: odizanje oslono-kretnog mehanizma c_1 , ugao okretanja platforme c_2 , pritisci p_{21} , p_{22} u radnim vodovima hidromotora pogona platforme, hodovi c_i ($i=3,4,5$) hidrocilindara i pritisci p_{i1} , p_{i2} u radnim vodovima hidrocilindara pogonskih mehanizama: strele, ruke i kašike manipulatora.

Geometrijske veličine. - Generalisana koordinata položaja oslono kretnog mehanizma određena je jednačinom (sl.2):

$$\theta_1 = \begin{cases} -\arctg \frac{2 \cdot c_1}{L + 2 \cdot a_1} & \forall c_1 \geq 0 \\ -\arctg \frac{2 \cdot c_1}{2 \cdot a_1 - L} & \forall c_1 \leq 0 \end{cases} \quad (3)$$

gde je: c_1 - veličina odizanja oslono-kretnog mehanizma, a_1 - koordinata položaja davača odizanja oslono-kretnog mehanizma, L - dužina naleganja gusenica.

Zavisno od izmerenih veličina c_i , ($i=3,4,5$) korišćenjem prenosnih funkcija pogonskih mehanizama, određuju se ostale generalisane koordinate θ_i položaja članova kinematičkog lanca manipulatora.

Dvostrukim diferenciranjem generalisanih koordinata, određuju se ugaone brzine $\dot{\theta}_i$ i ugaona ubrzanja $\ddot{\theta}_i$ u zglobovima O_i članova kinematičkog lanca bagera:

$$\dot{\theta}_i = \frac{\theta_{i(t+\Delta t)} - \theta_{i(t-\Delta t)}}{2\Delta t} \quad (4)$$

$$\ddot{\theta}_i = \frac{\theta_{i(t+2\Delta t)} - 2\theta_{i(t)} + \theta_{i(t-2\Delta t)}}{4\Delta t^2} \quad \forall i = 2,3,4,5 \quad (5)$$

gde je: $\theta_{i(t)}$ - generalisane koordinate u trenutku t trajanja ciklusa, $\theta_{i(t+\Delta t)}$, $\theta_{i(t-\Delta t)}$, $\theta_{i(t+2\Delta t)}$, $\theta_{i(t-2\Delta t)}$ - generalisane koordinate u trenutku vremena koje je za jedan ili dva intervala vremena Δt veće ili manje od vremena t , Δt - interval vremena između dva uzastopna merenja veličina.

Kinematičke veličine. - Linearne v_i i ugaone ω_i brzine i linearna w_i i ugaona ε_i ubrzanja za središta mase člana L_i kinematičkog lanca određeni su rekurzivnim jednačinama [2][3]:

$$\omega_i = \omega_{i-1} + \dot{\theta}_i \cdot e_i \quad (6)$$

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

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

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

gde je: $\dot{\theta}_i, \ddot{\theta}_i$ - ugaona brzina i ugaono ubrzanje člana L_i u zglobovima O_i .

Dinamičke veličine. - Dinamičke veličine člana L_i : inercijalna sila F_i i moment inercijalnih sila M_i određuju se Newton- Euler-ovim dinamičkim jednačinama:

$$F_i = -m_i w_i \quad (10)$$

$$M_i = -J_i \varepsilon_i + (\omega_i \times J_i \omega_i) \quad (11)$$

Ukupna sila vezana za središte mase člana L_i , uzimajući i uticaj gravitacije, jednaka je:

$$F_{ui} = F_i + m_i g \quad (12)$$

Na osnovu definisanog matematičkog modela razvijen je program za analizu parametara pogona obrtne platforme bagera na osnovu izmerenih veličina stanja bagera pri radu u eksploatacionim uslovima.

3. ANALIZA

Na osnovu merenih veličina stanja ispitivanog hidrauličkog bagera guseničara, mase 16000 kg, opremljenog sa dubinskim manipulatorom zapremine kašike 0,6 m³, korišćenjem razvijenog programa, izvršena je analiza parametara pogonskog mehanizma obrtne platforme bagera. Rezultati analize su dati za tri manipulaciona zadatka (I, II, III) sa dubinama kopanja: 0,5, 1,5 i 3,5 m, uglom okretanja platforme 35° i visinom istovara oko 3,5 m [4].

Kao rezultati analize parametara pogonskog mehanizma platforme dati su dijagrami promena:

a) kinematičkih parametara - ugaonih brzina (sl.3a) i ugaonih ubrzanja (sl.3b) i

b) dinamičkih parametara - momenta (sl.4a), snage (sl.4b) i oprećenja aksijalnog ležaja (sl.5) pogonskog mehanizma obrtne platforme ispitivanog bagera.

Slika 3. Kinematički parametri: a) ugaone brzine i b) ugaona ubrzanja obrtne platforme ispitivanog bagera tokom manipulacionih zadataka I, II i III

Kinematički parametri obrtne platforme bagera, kako dijagrami (sl.3a,b) pokazuju, pri operaciji prenosa materijala iz ravni kopanja u ravan istovara i pri operaciji vraćanja u novu ravan kopanja materijala imaju karakterističnu promenu sa fazama ubrzanog, približno ravnomernog i usporenog obrtnog kretanja [5].

Pri istim operacijama, nagle promene kinematike kretanja, prate i nagle promene dinamičkih parametara - pogonskih momenata M_{2y} i potrebne snage N_{2y} okretanja platforme bagera određenih jednačinama:

$$M_{2y} = \text{sign}(\dot{\theta}_2) \cdot i_{r2} \frac{d_2}{2\pi} (p_{21} - p_{22}) \quad (13)$$

$$N_{2y} = M_{2y} \cdot \dot{\theta}_2 \quad (14)$$

gde je: i_{r2} - prenosna funkcija pogonskog mehanizma obrtne platforme, d_2 - specifični protok hidromotora pogonskog mehanizma obrtne platforme.

Skokovite promene pogonskog momenta okretanja platforme se javljaju na početku okretanja platforme kada je potrebno iz ravni kopanja ubrzano pokrenuti obrtnu platformu, manipulator i kašikom zahvaćeni materijal, koji u odnosu na osu okretanja platforme imaju veliki moment inercije.

Karakteristične su znatne negativne vrednosti snage (sl.4b) nastale u fazi usporenog kretanja (zaustavljanja) obrtne platforme tokom manipulacionog zadatka bagera. Ova snaga se kod konvencionalnih pogonskih sistema bagera frikcionim kočenjem gubi (pretvara u toplotu), a kod savremenih (hibridnih) pogonskih sistema rekuperacijom ponovo akumulira i vraća pogonskom sistemu bagera.

Slika 4. Dinamički parametri: a) pogonski momenti i b) snaga pogonskog mehanizma obrtne platforme ispitivanog bagera tokom manipulacionih zadataka I, II i III

Analiza opterećenja aksijalnog ležaja pogonskog mehanizma obrtno platforme bagera je izvršena na osnovu komponenata rezultujuće sile F_2 i rezultujućeg momenta M_2 , određenih, iz uslova ravnoteže za zglobov O_2 kinematičkog lanca bagera (sl.5), pomoću jednačina [6] [7]:

$$F_2 = -W - \sum_{i=2}^5 F_{ui} - F_{c2} \quad (15)$$

$$M_2 = ((r_w - r_2) \times W) + \sum_{i=2}^5 ((r_w - r_2) \times F_{ui}) + \sum_{i=2}^5 M_{ui} \quad (16)$$

gde je: W - vektor otpora kopanja određen na osnovu merenih veličina stanja rada bagera u eksploatacionim uslovima [8], F_{c2} - sila reakcije ozubljenog venca aksijalnog ležaja.

Za ispitivani model bagera, izvršena je analiza opterećenja aksijalnog ležaja pogona okretanja platforme za merene veličine stanja rada bagera tokom manipulacionih zadataka I. Rezultati analize su dati, u obliku dijagrama promene statičkih F_{2xs}, F_{2zs} (sl.5a) i dinamičkih F_{2xd}, F_{2zd} komponenata sile i statičkih M_{2xs}, M_{2zs} (sl.5b) i dinamičkih M_{2xd}, M_{2zd} komponenata momenta opterećenja aksijalnog ležaja pogona obrtno platforme. Kako dijagrami pokazuju, statička i dinamička opterećenja aksijalnog ležaja se u većem delu procesa kopanja, malo razlikuju, što pokazuje, da je dinamički uticaj usled kretanja članova kinematičkog lanca bagera pri procesu kopanja mali jer se i sam proces kopanja odvija relativno sporo. Do dinamičkog uticaja na opterećenje ležaja dolazi, na početku i kraju procesa kopanja, kada istovremeno nastaje odizanje (pomeranje) guseničnog oslonog člana, što izaziva i pojavu povećanih dinamičkih sila i momenata kod svih članova kinematičkog lanca bagera.

Slika 5. Opterećenja aksijalnog ležaja pogonskog mehanizma obrtno platforme pri manipulacionom zadatku I:
a) komponente statičkih F_{2xs} , F_{2ys} , F_{2zs} i dinamičkih F_{2xd} , F_{2yd} , F_{2zd} sila, b) komponente statičkih M_{2xs} , M_{2zs} i dinamičkih M_{2xd} , M_{2zd} momenata.

Do pojave povećanih dinamičkih opterećenja ležaja dolazi na početku i kraju operacija prenosa zemljišta i povratka na novu ravan kopanja usled pokretanja platforme bagera kada se ubrzavaju i usporavaju mase članova kinematičkog lanca manipulatora koje nosi obrtna platforma bagera.

Dinamičke promene opterećenja ležaja nastaju i pri operaciji istovara usled nagle promene dinamičkih parametara smanjenjem mase zemljišta pri pražnjenju kašike.

Tokom trajanja manipulacionih zadataka bagera najveće vrednosti komponenta sile (sl.5a), i momenta (sl.5b) opterećenja aksijalnog ležaja, merodavni za izbor veličine ležaja, javljaju se pri operaciji kopanja.

4. ZAKLJUČAK

U radu je data analiza kinematičkih i dinamičkih parametara pogonskog mehanizma obrtno platforme hidrauličkih bagera zasnovane na merenim veličinama stanja rada fizičkog modela bagera u eksploatacionim uslovima.

Rezultati kinematičke analize ugaone brzine okretanja platforme pokazuju da pri prenosu materijala obrtno kretanje platforme ima faze kratkotrajnog ubrzanog, ravnomernog i usporenog kretanja. Rezultati analize ukazuju da je pogonski mehanizam obrtno platforme vrlo dinamičan sistem. Dinamičnost se ogleda u naglim promenama momenta pokretanja i zaustavljanja sistema koji ima veliki i promenljivi moment inercije obrtnih masa (platforma, članovi kinematičkog lanca manipulatora, kašikom zahvaćeni materijal). Posledice nagle promene momenata okretanja platforme nastaju, pri fazama pokretanja i zaustavljanja, usled stišljivosti hidrauličkog ulja, pri čemu ulje u radnim vodovima hidromotora ima karakteristike hidrauličkih opruga.

Obavljena istraživanja, čiji je deo prikazan u ovom radu, predstavljaju prilog analizi definisanja karaktera promene opterećenja ležaja pogona okretanja obrtno platforme hidrauličkih bagera tokom procesa kopanja sa manipulatorom dubinske kašike. Analize pokazuju da se najveća opterećenja, merodavna za pravilan izbor ležaja, po kriterijumima svetskih proizvođača ležaja, javljaju pri operaciji kopanja bagera. Važnost poznavanja vektora opterećenja ležaja čini osnov neophodnih mehaničkih, energetskih i strukturnih simulacija i analiza u cilju optimizacije strukturne građe i pogonskih mehanizama bagera. Razvijeni softver i skup merenih veličina dobijenih tokom obavljenih ispitivanja hidrauličkog bagera, može se iskoristiti ne samo za definisanje vektora opterećenja ležaja nego i za ostale dinamičke analize bagera.

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Experimental Analysis of the Parameters of the Slewing Platform Drive Mechanism of Hydraulic Excavators

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This paper presents a method for experimental determining the parameters of the slewing platform drive mechanism of the hydraulic excavators with backhoe manipulator. It is defined the dynamic mathematical model that allows, indirectly, determine kinematic and dynamic parameters of the slewing platform drive mechanism of excavator, based on measured values condition excavator at work in the exploitation conditions. Obtained results show extremely dynamic changes of parameters of hydrostatic part of the driving mechanism of the slewing platform in operation of transmission materials. The analysis shows that the largest load of slewing bearing drive occurring in the operation of digging.

Keywords: hydraulic excavators, slewing platform, examination

1. INTRODUCTION

The necessary spatial manipulation of hydraulic excavators provides first kinematic pair in general configurations of machines kinematic chain which build: support and movement mechanism and slewing platform connected rotary joint of the fifth class in the form of a slewing bearing. Relying on surface, support and movement mechanism is relatively stationary member relative to a slewing platform that could achieve a rotation in both directions around the vertical axis of the joint.

The general model of the slewing platform drive mechanism of excavator consists of: hydraulic motor 5 (Fig.1), reducer 6 with a gear 6.1 on the output shaft and slewing bearing 7 with an inner ring gear 7.1 and a toothless outer ring 7.2.

Hydraulic motor drive is powered by double flow hydraulic pump 3.1 driven by a diesel engine 1. Regulation hydraulic pump by the control distributor 4.1 achieves change the rotational direction of the platform.

The synthesis of the complete drive mechanism of a hydraulic excavator rotating platform is performed by the following procedure:

Figure 1. Slewing platform drive of hydraulics excavator

a) selection of the concept drive solution, b) selection of the slewing bearing based on a detailed analysis of load bearing in the whole working area machines, c) selection of hydraulic motor, gear unit and hydraulic pump of slewing drive, d) definition of attachment elements and elements of the support structure to which the bearing is attached. For optimal synthesis of drive rotation platform requires knowledge of kinematic and dynamic parameters of the drive.

2. MATHEMATICAL MODEL

In this paper presents the method for experimental analysis of kinematic and dynamic parameters of the drive platform excavators on the basis of the measured quantities of the state when the machine operates under real-exploitation conditions. The method of experimental analyzes of the platform is based on developed dynamic mathematical model of excavator with five configuration of kinematic chain, composed of: support and movement member L_1 (Fig.2), slewing member (slewing platform) L_2 and three-member planar manipulator with: boom L_3 , stick L_4 and bucket L_5 .

Set size, the mathematical model of the excavator are covered (Fig. 2) [1] [2]:

parameters of excavator members kinematic chain

$$L_i = \{e_i, s_i, t_i, m_i, J_i\} \quad \forall i = 1, \dots, 5 \quad (1)$$

and parameters of drive mechanisms of excavator:

$$C_i = \{d_i, a_i, b_i, m_{ci}\} \quad \forall i = 1, \dots, 5 \quad (2)$$

where: e_i - the unit vector of joint O_i axis which connects member L_i to the previous member L_{i-1} , s_i - the vector of the position of joint O_{i+1} center which is used to connect the chain member L_i to the next member L_{i+1} , t_i - the vector of the position of the member mass center, m_i - the member mass, J_i - the tensor of the member moment of inertia, d_i - parameters size actuators (hydraulic motor and hydrocylinder) drive mechanisms; a_i , b_i - vector of position of joint in which actuators linked for kinematics chain of excavator, m_{ci} - mass of drive mechanisms.

Figure 2. Mathematical model of excavator for experimental examination parameters of slewing platform drive

The measured quantities of the state of the kinematic chain excavators are: lifting of support and movement mechanism c_1 , pressure p_{21} , p_{22} in working duct of the hydraulic motor of slewing platform drive, strokes c_i ($i=3,4,5$) of hydro cylinders and pressures p_{i1} , p_{i2} in working ducts of hydro cylinder drive mechanisms of: boom, stick and bucket.

Geometric quantities. - The generalized coordinate positions of support and movement mechanism is determined by the equation (Fig. 2):

$$\theta_1 = \begin{cases} -\arctg \frac{2 \cdot c_1}{L + 2 \cdot a_1} & \forall c_1 \geq 0 \\ -\arctg \frac{2 \cdot c_1}{2 \cdot a_1 - L} & \forall c_1 \leq 0 \end{cases} \quad (3)$$

where: c_1 - the size of lifting support and movement mechanism, a_1 - coordinate position encoder lifting support and movement mechanism, L - length footprint caterpillars. Depending on the measured electric quantities c_i , ($i=3,4,5$) using transfer functions of driving mechanisms, determine the other generalized coordinates position of the members of the kinematic chain manipulators.

Double differencing of generalized coordinates, determined the angular velocity and angular acceleration of the joints O_i members kinematic chain excavators:

$$\dot{\theta}_i = \frac{\theta_{i(t+\Delta t)} - \theta_{i(t-\Delta t)}}{2\Delta t} \quad (4)$$

$$\ddot{\theta}_i = \frac{\theta_{i(t+2\Delta t)} - 2\theta_{i(t)} + \theta_{i(t-2\Delta t)}}{4\Delta t^2} \quad \forall i = 2,3,4,5 \quad (5)$$

where: $\theta_{i(t)}$ - generalized coordinates at time t of cycle, $\theta_{i(t+\Delta t)}$, $\theta_{i(t-\Delta t)}$, $\theta_{i(t+2\Delta t)}$, $\theta_{i(t-2\Delta t)}$ - generalized coordinates in moment of time that is for one or two time intervals Δt greater or less than the time t , Δt - the time interval between two successive measured quantities.

Kinematic quantities. - The linear v_i and angular ω_i velocity and linear w_i and angular ε_i acceleration for the center of mass member L_{ii} of the kinematic chain are determined by recursive equations [2] [3]:

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

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

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

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

where: $\dot{\theta}_i, \ddot{\theta}_i$ - angular velocity and angular acceleration member L_i in joint O_i .

Dynamic quantities. - Dynamic quantities member

L_i : inertial force F_i and moment of inertial forces M_i determined by *Newton-Eyler's* dynamic equations:

$$F_i = -m_i w_i \quad (10)$$

$$M_i = -J_i \varepsilon_i + (\omega_i \times J_i \omega_i) \quad (11)$$

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

$$F_{ui} = F_i + m_i g \quad (12)$$

On the basis of a defined mathematical model is developed programm for analyzing parameters of slewing platform drive mechanism of excavators based on the measured quantity of state excavator at work in operating conditions.

3. ANALYSIS

Based on the measured quantities of the state of the investigated hydraulic crawler excavators, weighing *16000 kg*, equipped with bachoe bucket volume *0,6 m³*, using the developed program, is performed analysis of parameters of slewing platform drive mechanism of excavators. The analysis results are given for three manipulating task (I, II, III) with digging depth: *0,5, 1,5 и 3,5 m*., angle of rotation platform *35°* and unloaded height about *3,5 m* [4].

As results of the analysis parameters of slewing platform drive mechanism, give the diagrams of changes:

a) kinematic parameters - angular velocity (Fig. 3a) and angular acceleration (Fig.3b) and

b) dynamic parameters - torque (Fig. 4a), power (Fig. 4b) and slewing bearing loads (Fig. 4b) platform drive mechanism of the investigated excavators.

Figure 3. Kinematic parameters: a) the angular velocity and b) the angular acceleration of the platform investigated excavator during manipulation tasks I, II and III

The kinematic parameters excavator slewing platform, as diagrams show (Fig. 3a,b), in the operation of transmission of material from the digging level in the unloading plane and in return operations to a new digging plane, having a characteristic change with the phase of accelerated, approximately uniform and slow slewing motion [5].

At the same operations, sudden changes in the kinematics of movement, monitor and sudden changes in dynamic parameters - driving moment M_{2y} and required power N_{2y} rotation platform, determined by equations:

$$M_{2y} = \text{sign}(\dot{\theta}_2) \cdot i_{r2} \frac{d_2}{2\pi} (p_{21} - p_{22}) \quad (13)$$

$$N_{2y} = M_{2y} \cdot \dot{\theta}_2 \quad (14)$$

where: i_{r2} - the transfer function of slewing platform drive mechanism, d_2 - specific flow hydraulic motor slewing platform drive mechanism.

Surging changes of the slewing platform drive moment occurring at the beginning of rotation platform, when required, from the digging level accelerated start slewing platform, manipulator and caught material by bucket, which, in relation to the axis of rotation platform have a great moment of inertia.

The characteristic significant negative values of power (Fig.4b) incurred in the phase of slow movement (stopping) slewing platform during manipulative task excavator. This power is in the conventional drive system excavator, by friction braking, lost (converted into heat), but in modern (hybrid) drive systems recovery again accumulates and returns drive system excavators.

Figure 4. Dynamic parameters: a) drive moment and b) the power of the slewing platform drive mechanism of excavator during manipulation tasks I, II and III

Analysis of slewing bearing load of slewing platform drive mechanism excavators was performed on the components of the resulting force F_2 and the resulting moment M_2 , certain, from the equilibrium condition for joint O2 of kinematic chain excavators (Fig.2), using the equation [6] [7]:

$$F_2 = -W - \sum_{i=2}^5 F_{ui} - F_{c2} \quad (15)$$

$$M_2 = ((r_w - r_2) \times W) + \sum_{i=2}^5 ((r_w - r_2) \times F_{ui}) + \sum_{i=2}^5 M_{ui} \quad (16)$$

where: W - vector digging resistance determined on the basis on measured quantities of the state when the machine operates under real-exploitation conditions [8], F_{c2} - reaction force toothed wreath slewing bearing.

For investigated model of excavator, slewing bearing load of slewing platform drive mechanism excavators was performed basis on measured quantities of the state during manipulative task I. Results of the analysis are given in the form of a diagram change static F_{2xs}, F_{2zs} (Fig.4a) and dynamic F_{2xd}, F_{2zd} components of force and static M_{2xs}, M_{2zs} (Fig.4b) and dynamic M_{2xd}, M_{2zd} components of moment slewing bearing load of slewing platform drive mechanism.

How diagrams show the static and dynamic load slewing bearing for the most part they began digging, a little different, which shows that the dynamic impact due to the movement of members of the kinematic chain excavator in the process of digging small, because the process of digging takes relatively slowly. By the dynamic effect of the load bearing comes at the beginning and end of the process of digging, when simultaneously formed lifting (displacement) support and movement member, which causes the appearance of increased dynamic forces and moments in all members of the kinematic chain excavator.

Figure 5. The load of slewing platform drive mechanism in operating task I: a) components static $F_{2xs}, F_{2ys}, F_{2zs}$ and dynamic $F_{2xd}, F_{2yd}, F_{2zd}$, b) komponente M_{2xs}, M_{2zs} static, and dynamic M_{2xd}, M_{2zd} moments.

Until the advent of increased dynamic bearing load comes at the beginning and end of the operation the transfer of soil and returning to a new digging level due to start of rotating excavator platforms when the speeding up and slowing down the mass of the members of the kinematic chain manipulator that carries the slewing platform excavator.

Dynamic changes bearing load occurring and in the operation of unloading due to sudden changes in dynamic parameters by reducing the weight of the soil, when emptying buckets. During manipulative tasks excavator, highest values of force components (Fig. 5a), and torque (Fig. 5b) load slewing bearing, applicable to selection size bearing occur in the operation of digging.

4. CONCLUSION

The paper presents analysis of kinematic and dynamic parameters of the slewing platform drive mechanism of hydraulic excavator based on the measured quantity of state working physical excavator model in the exploitation conditions.

Results kinematic analysis of angular velocity platforms show that in the transfer of material slewing motion of the platform has a short phase of accelerated, uniform and slow slewing movement.

Results of the analysis indicate that the drive mechanism of the platform is very dynamic system. Dynamism is reflected in the rapid changes in moment start and stop system that has a large and variable moment of inertia of rotating masses (platform, members of kinematic chain manipulator, caught material by bucket). The consequence of sudden changes in moment slewing platform created in stages starting and stopping, due to the compressibility of the hydraulic oil, whereby the oil in the working lines of the hydraulic motor has the characteristics of the hydraulic spring.

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 program 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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