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ANALYSIS OF SLEWING BEARING LOAD OF A ROTATING PLATFORM DRIVE IN HYDRAULIC EXCAVATORS

Vesna Jovanović, Dragoslav Janošević, Nikola Petrović

Original scientific paper

The paper presents the selection procedure of a slewing bearing of a rotating platform drive in hydraulic excavators with a shovel attachment based on the spectrum of equivalent bearing loads. In line with the developed mathematical model of the excavator, the spectrum of equivalent bearing loads is defined according to boundary digging resistances which allow for the stability of the excavator and boundary digging resistances which can be overcome by excavator drive mechanisms. Software was developed to enable the determination and detailed analysis of slewing bearing load in the entire working range of the excavator since the same excavator model can be equipped with various working tools which can occupy numerous different positions under a variety of working conditions. The paper provides spectra of equivalent bearing loads of the rotating platform drive in a hydraulic excavator, obtained by using the developed software.

Keywords: *hydraulic excavators, rotating platform drive, slewing bearing load*

Analiza opterećenja aksijalnog ležaja pogona okretne platforme hidrauličnih bagera

Izvorni znanstveni članak

U radu je dan postupak izbora aksijalnog ležaja pogona okretne platforme hidrauličnih bagera s utovarnim manipulatorom na temelju spektra ekvivalentnih opterećenja ležaja. Prema razvijenom matematičkom modelu bagera, spektar ekvivalentnih opterećenja ležaja definiran je na temelju graničnih otpora kopanja koje dopušta stabilnost bagera i graničnih otpora kopanja koje mogu svladati pogonski mehanizmi bagera. Razvijen je softver koji omogućava određivanje i detaljnu analizu opterećenja aksijalnog ležaja u cijelom radnom području bagera s obzirom de se isti model bagera može opremiti različitim izvršnim alatima koji mogu imati mnoštvo različitih položaja i uvjeta rada. Dani su spektri ekvivalentnih opterećenja ležaja pogona okretne platforme hidrauličkog bagera dobiveni uporabom razvijenog softvera.

Ključne riječi: *hidraulični bageri, opterećenje aksijalnog ležaja, pogon obrtne platforme*

1 Introduction

The primary function of hydraulic excavators, of all sizes, is the cyclic excavation and transport of various materials. Hydraulic excavators perform their primary function of digging through a general configuration of the kinematic chain which consists of the support and movement mechanism L_1 (Fig. 1b,c), rotating platform L_2, and changeable multi-member manipulators L_m, which can be equipped with numerous tools in the form of buckets, claws, grapples, tillers, hammers, hooks (Fig. 1a). For digging operations below the ground level, the toward oneself technology (in relation to the excavator operator) is employed and a backhoe attachment is used (Fig.1b). For digging operations above the ground level the away from oneself technology and a shovel attachment are used (Fig.1c). Hydraulic excavators perform spatial manipulation using the rotating platform L_2 (Fig.1b,c), which is attached to the support and movement mechanism L_1 by way of a rotary joint, of the fifth class, in the form of a slewing bearing. The rotating drive mechanism of the platform consists of a hydraulic motor 1 (Fig. 1d), a reducer 2 coupled over an output gear 2.1 with a ring gear of a slewing bearing 3.1. By rule, a slewing bearing 3 (Fig. 1d) consists of an inner ring gear 3.1, which is bolted to the support and movement mechanism L_1, and a toothless outer ring 3.2, which is bolted to the rotating platform L_2. Rolling elements (balls, rollers) are positioned between the rings in one or more races.

The synthesis of the complete drive mechanism of a hydraulic excavator rotating platform is performed by the following procedure: a) selection of the concept drive solution, b) selection of the slewing bearing, c) definition of attachment elements and elements of the support structure to which the bearing is attached, d) selection of the hydraulic motor and rotating drive reducer. In the design of the basic excavator systems, research was conducted into: 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, 9].

Research into rotating drive mechanisms of excavator platforms deals with: a) loads of slewing bearing rolling elements [10, 11], b) analysis of slewing bearing loads in excavators with excavating manipulators [12], and c) regulation of angular velocity of a rotating platform [13 ÷ 16].

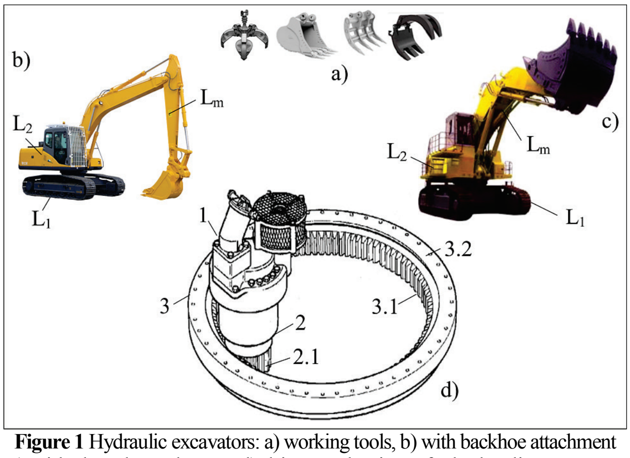

Figure 1 Hydraulic excavators: a) working tools, b) with backhoe attachment c) with shovel attachment, d) drive mechanism of a hydraulic excavator rotating platform

For a reliable selection of a slewing bearing of a rotating platform in a hydraulic excavator, of a certain size, it is necessary to determine the spectra of bearing loads for all possible configurations of kinematic chains that the excavator is equipped with. These possible configurations of kinematic chains differ from the variants of support and movement mechanisms, then the variants of manipulator members, and the tools which the excavator uses. Furthermore, it is also necessary to determine the spectrum of bearing loads for the same configuration of the excavator kinematic chain in as many positions of the entire working range of the excavator as possible, having in mind that each position of the kinematic chain carries the possibility of the action of the digging resistance in various directions depending on the excavator working conditions.

This paper provides a selection procedure for the size of a slewing bearing of a rotating platform drive in hydraulic excavators with a shovel attachment, based on the spectrum of equivalent bearing loads.

2 Mathematical model of the excavator

The mathematical model encompasses a five-member configuration of the excavator kinematic chain comprising: support and movement mechanism L_1 (Fig. 2), rotating platform L_2, and a three-member planar shovel attachment with: boom L_3, stick L_4 and bucket L_5. The space of the excavator model is determined with an absolute coordinate system OXYZ and unit vectors. The excavator support surface lies in the horizontal plane OXZ of the absolute coordinate system, while the vertical axis OY of the same system overlaps with the axis of the slewing bearing of the rotating platform drive mechanism. Members of the excavator kinematic chain compose kinematic pairs of the fifth class - rotary joints with one degree of freedom. The centre of joint O_2 of the kinematic pair composed of the support and movement mechanism and the rotating platform is the point of perpendicular intersection of the vertical axis of the joint through the horizontal plane where the centres of rolling elements of the rotating platform drive mechanism slewing bearing are positioned. The centres of manipulator joints O_i are points of intersection of the horizontal axis of joints through the plans of symmetry of the excavator manipulator kinematic chain. The intersection of the bucket cutting edge through the plane of manipulator represents the centre of the bucket cutting edge O_w.

The assumptions of the mathematical model of the excavator are: 1) the support surface and kinematic chain members are modelled using rigid bodies, 2) the first joint of the kinematic chain between the movement mechanism surface represents a polygon bounded by potential longitudinal $x-x$ (Fig. 2) and transverse $z-z$ excavator rollover lines. Inside the polygon, the first joint has the shape of a translator -sliding joint, while on the edges of the polygon it has the shape of rotary joints O_{11}, O_{12}, whose axes represent potential excavator rollover lines, 3) during the manipulation task the work of the excavator is stable, i.e. there are no potential movements in the first joint, 4) during the digging operation the kinematic chain of the excavator has an open configuration subjected to: a) gravitational forces (weights) of: kinematic chain members, members of the drive system and material scooped by the bucket and b) digging resistance W in the centre of the bucket cutting edge O_w, the position of the hydraulic cylinders mass centres is in the middle of the current length of hydraulic cylinders, 5) masses of joint elements belong to the members of the manipulator kinematic chain, 6) the influence of friction is neglected in the kinematic chain joints and drive mechanism joints.

Each member of the excavator kinematic chain L_i is determined, in its local coordinate system $O_i\, x_i\, y_i\, z_i$, with a set of quantities [12]:

$$L_i = \left\{ \hat{\vec{e}}_i, \hat{\vec{s}}_i, \hat{\vec{t}}_i, m_i \right\} \quad \forall i = 1, 2, 3, 4, 5, \tag{1}$$

where: $\hat{\vec{e}}_i = \left\{ e_{ix}, e_{iy}, e_{iz} \right\}$ - the unit vector of joint O_i axis which connects member L_i to the previous member L_{i-1}, $\hat{\vec{s}}_i = \left\{ s_{ix}, s_{iy}, s_{iz} \right\}$ - 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 s_i magnitude represents the kinematic length of the member), $\hat{\vec{t}}_i = \left\{ t_{ix}, t_{iy}, t_{iz} \right\}$ - the vector of the position of the member mass centre, - the member mass. Quantities marked with a 'cap' above the symbol are determined in the local coordinate system of the member. The mathematical model of the excavator drive system encompasses the drive mechanisms of manipulator boom, stick, and bucket, which have two-way hydraulic cylinders c_3, c_4 and c_5 as actuators (Fig. 2). Each drive mechanism C_i of the excavator manipulator is determined using a set of quantities:

$$C_i = \left\{ d_{i1}, d_{i2}, c_{ip}, c_{ik}, \hat{\vec{a}}_i, \hat{\vec{b}}_i, m_{ci}, n_{ci} \right\} \quad \forall i = 3, 4, 5, \tag{2}$$

where: d_{i1}, d_{i2} - the diameter of the piston and piston rod of the hydraulic cylinder, c_{ip}, c_{ik} - the initial and final length of the hydraulic cylinder, $\hat{\vec{a}}_i, \hat{\vec{b}}_i$ - the vectors of the position of joint centres where the hydraulic cylinder is connected to the kinematic chain members, m_{ci} the mass of the hydraulic cylinder, n_{ci} - the number of hydraulic cylinders of the drive mechanism.

The digging resistance vector is determined with the equation:

$$\vec{W} = W_\mathrm{r} \cos\varphi_\mathrm{w} \vec{i} + W_\mathrm{r} \sin\varphi_\mathrm{w} \vec{j} + W_\mathrm{b} \vec{k}, \tag{3}$$

where: W_r - the digging resistance which acts in the plane of the manipulator, W_b - the lateral digging resistance, φ_w - the angle of the direction in which the digging resistance W_r acts in relation to the horizontal OXZ plane of the absolute coordinate system.

The direction in which the digging resistance W_r acts in relation to the horizontal OXZ plane of the absolute coordinate system is determined with the angle:

$$\varphi_\mathrm{w} = \sum_{i=3}^{5} \theta_i + \theta_\mathrm{w}, \tag{4}$$

where: θ_i (i=3, 4, 5) - the angle of the relative position of member L_i in relation to the previous member L_{i-1} upon the rotation around the axis of joint O_i by changing the length c_i of the drive mechanism hydraulic cylinder, θ_w - the angle of the direction in which the digging resistance acts in relation to the positive O_5x_5 axis of the local coordinate system of the bucket L_5.

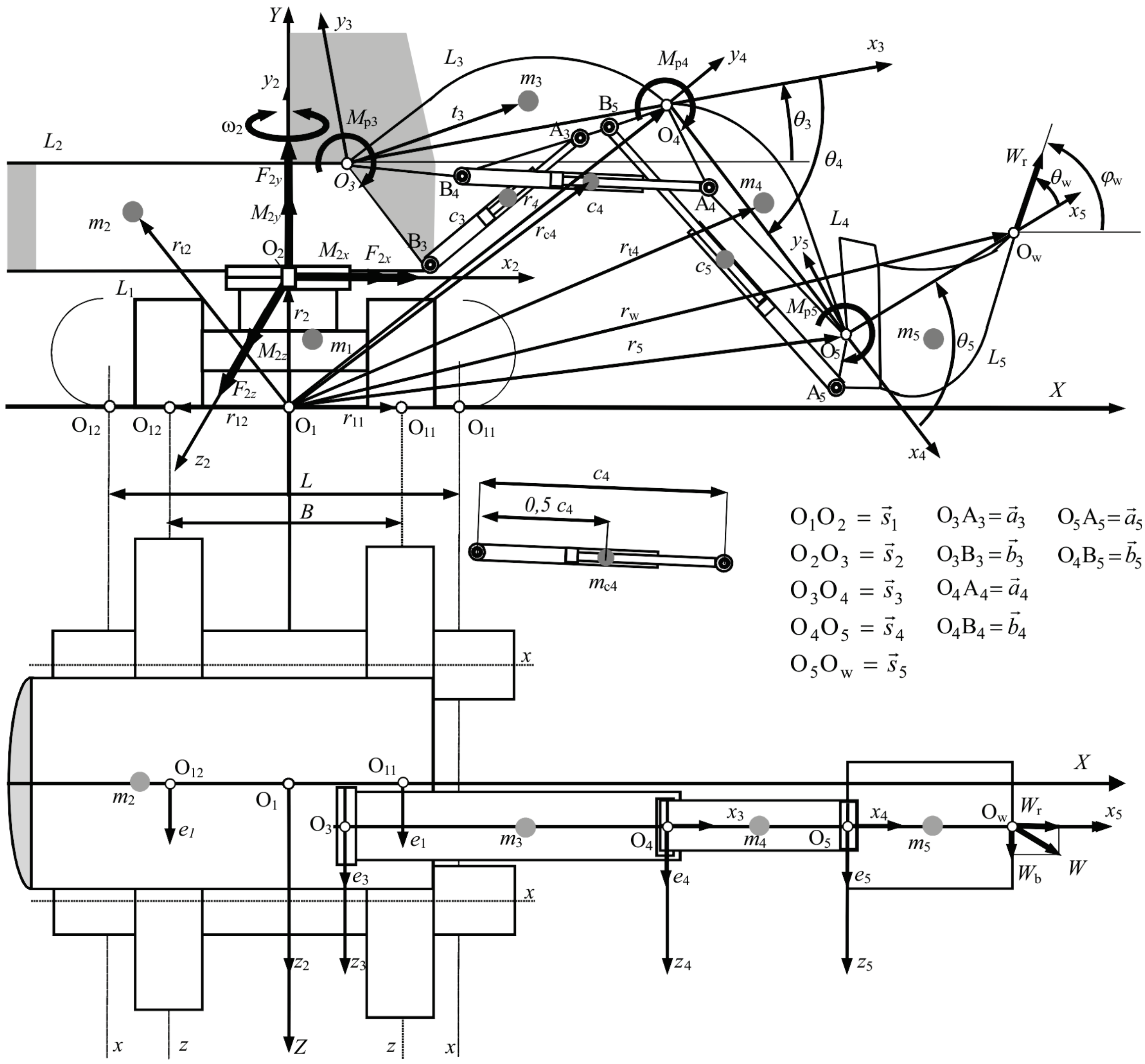

Figure 2 Determining the load of axial bearing slewing platforms of hydraulic excavator with a shovel attachment

The magnitude of the digging resistance W_r vector, for a particular direction of action, is defined by the equation:

$$W_r = \min\{W_o, W_1, W_3, W_4, W_5\}, \tag{5}$$

where: W_o - the highest boundary digging resistance determined from the excavator non-sliding conditions in the plane of the support surface, W_1 - the highest boundary digging resistance determined from the given excavator stability conditions for potential rollover lines, W_3, W_4, W_5 - are the highest boundary values of the digging resistance which can be overcome by the drive mechanisms of manipulator boom, stick, and bucket at the maximum pressure of the excavator hydraulic system.

The unit vector of the digging resistance W_r:

$$ort\vec{W}_r = \cos\varphi_w \vec{i} + \sin\varphi_w \vec{j}. \tag{6}$$

The boundary digging resistance W_o bounded by the force of adherence of the excavator to the support surface is determined from the balance conditions of the sliding part of the first joint, i.e. from the condition that the support and movement mechanism of the excavator will not slide, during digging, along the support surface:

$$W_o = \frac{mg \cdot \mu_p}{|\cos\varphi_w|}, \tag{7}$$

where: m - the total mass of the excavator, μ_p - the coefficient of adherence of the excavator movement mechanism to the support surface.

Depending on the position of the kinematic chain of the excavator and $ort\vec{W}_r$, the boundary digging resistance W_1, which is limited by the static stability of the excavator, is determined from the balance conditions for one of the rotary joints O_{11}, O_{12}, whose axes represent the potential excavator rollover lines (Fig. 2):

$$W_1 = \begin{cases} W_{11} = \dfrac{-M_{\text{o}11}}{\left((\vec{r}_\text{w} - \vec{r}_{11}) \times ort\vec{W}_\text{r}\right) \cdot \vec{e}_1}, \\ \forall\ y_\text{w} > 0,\ \varphi_{12} > \varphi_\text{w} > (\varphi_{11} + 180°), \\ \forall\ y_\text{w} < 0,\ \varphi_{11} > \varphi_\text{w} > (\varphi_{12} + 180°), \\ W_{12} = \dfrac{-M_{\text{o}12}}{\left((\vec{r}_\text{w} - \vec{r}_{12}) \times ort\vec{W}_\text{r}\right) \cdot \vec{e}_1}, \\ \forall\ y_\text{w} > 0,\ (\varphi_{12} + 180°) > \varphi_\text{w} > \varphi_{11}, \\ \forall\ y_\text{w} < 0,\ (\varphi_{11} - 180°) > \varphi_\text{w} > \varphi_{12}, \end{cases} \tag{8}$$

where: $\vec{e}_1 = \{0,0,1\}$ - the unit vector of the first rotary joint (for the longitudinal x–x or transverse z–z excavator rollover line), $M_{\text{o}11}$, $M_{\text{o}12}$ - the gravitational moments for potential excavator rollover lines, i.e. rotary joints O_{11}, O_{12}, $\vec{r}_\text{w}$ - the vector of the position of the bucket cutting edge centre, $\vec{r}_{11}, \vec{r}_{12}$ - the vectors of the position of the centre of the appropriate first rotary joint O_{11}, O_{12}, y_w - the vertical coordinate of the bucket top, φ_{11}, φ_{12} - the angles of the position of vectors $(\vec{r}_\text{w} - \vec{r}_{11})$ and $(\vec{r}_\text{w} - \vec{r}_{12})$ in relation to the horizontal plane OXZ, determined by the equations:

$$\varphi_{11} = \arccos\left(\frac{(\vec{r}_\text{w} - \vec{r}_{11}) \cdot \vec{i}}{|\vec{r}_\text{w} - \vec{r}_{11}|}\right), \quad \varphi_{12} = \arccos\left(\frac{(\vec{r}_\text{w} - \vec{r}_{12}) \cdot \vec{i}}{|\vec{r}_\text{w} - \vec{r}_{12}|}\right). \tag{9}$$

Gravitational moments for potential excavator rollover lines, i.e. rotary joints O_{11}, O_{12}:

$$M_{\text{o}1} = \begin{cases} M_{o11} = -g\sum_{k=1}^{k=5} m_k \left((\vec{r}_{tk} - \vec{r}_{11}) \times \vec{j}\right) \cdot \vec{e}_1 - \\ \quad - g\sum_{k=3}^{k=5} m_{ck} \left((\vec{r}_{ctk} - \vec{r}_{11}) \times \vec{j}\right) \cdot \vec{e}_1 \\ M_{\text{o}12} = -g\sum_{k=1}^{k=5} m_k \left((\vec{r}_{tk} - \vec{r}_{12}) \times \vec{j}\right) \cdot \vec{e}_1 - \\ \quad - g\sum_{k=3}^{k=5} m_{ck} \left((\vec{r}_{ctk} - \vec{r}_{12}) \times \vec{j}\right) \cdot \vec{e}_1 \end{cases}, \tag{10}$$

where: m_k – the mass of the kinematic chain members, m_ck – the mass of the hydraulic cylinders, $\vec{r}_{tk}$ - the vector of the position of the kinematic chain member mass centre, $\vec{r}_{ctk}$ - the vector of the position of the hydraulic cylinder mass centre.

Boundary digging resistances W_i (i = 3, 4, 5) which can be overcome by the drive mechanisms of the manipulator, for the known $ort\vec{W}_\text{r}$ and the position of the excavator kinematic chain upon the action of the maximum drive moments $M_{\text{p}i}$, are determined from the balance conditions for the manipulator joints O_i axes (Fig. 2):

$$W_i = \frac{-M_{\text{p}i} - M_{ri}}{\left((\vec{r}_\text{w} - \vec{r}_i) \times ort\vec{W}\right) \cdot \vec{e}_i}, \ \forall i\text{=}3, 4, 5, \tag{11}$$

where: $M_{\text{p}i}$ - the maximum drive moments of manipulator mechanisms for both directions in which they act (upon piston pushing and piston pulling in the hydraulic cylinder), M_{ri} - the moment of gravitational forces of the kinematic chain members, members of the excavator drive mechanisms, and the mass of soil scooped by the full bucket, for certain axes of joints O_i, $\vec{r}_i$ - the vector of the position of the joint centre in the excavator kinematic chain, $\vec{e}_i = \{0,0,1\}$ - the unit vector of the joint axes in the manipulator kinematic chain.

The maximum drive moments of manipulator mechanisms for both directions in which they act (upon piston pushing and piston pulling in the hydraulic cylinder):

$$M_{\text{p}i} = \begin{cases} M_{\text{p}i1} = \text{sgn}(\dot{\theta}_i) r_{ci} n_{ci} \left[\dfrac{d_{i1}^2 \pi}{4} p_\text{m} - \dfrac{(d_{i1}^2 - d_{i2}^2)\pi}{4} p_\text{o}\right] \eta_{ci} \\ \forall i = 3, 4, 5;\ \dot{\theta}_3 > 0, \dot{\theta}_4 > 0, \dot{\theta}_5 > 0 \\ M_{\text{p}i2} = \text{sgn}(\dot{\theta}_i) r_{ci} n_{ci} \left[\dfrac{(d_{i1}^2 - d_{i2}^2)\pi}{4} p_\text{m} - \dfrac{d_{i1}^2 \pi}{4} p_\text{o}\right] \eta_{ci} \\ \forall i = 3, 4, 5;\ \dot{\theta}_3 < 0, \dot{\theta}_4 < 0, \dot{\theta}_5 < 0 \end{cases}, \tag{12}$$

where: $\dot{\theta}_i$ - the angular velocities of the kinematic chain members, r_{ci} - the transmission function of the drive mechanism which depends on the length of the hydraulic cylinder and the vector, i.e. coordinates, of the position of the joint centres where hydraulic cylinders are connected to the members of the drive mechanism kinematic chain [17], p_m - the maximum duct pressure during the extension stroke of the hydraulic cylinder, p_o - the maximum duct pressure during the retraction stroke of the hydraulic cylinder, η_{ci} - the mechanical degree of the hydraulic cylinder efficiency.

The moment of the gravitational forces of the kinematic chain members, members of the excavator drive mechanisms, and the mass of soil scooped by the full bucket, for certain axes of joints O_i, is determined by the equation:

$$M_{ri} = M_{\text{o}i} - gm_z \left((\vec{r}_{t5} - \vec{r}_i) \times \vec{j}\right) \cdot \vec{e}_i, \ \forall i = 1, 3, 4, 5, \tag{13}$$

where: M_{oi} - the moment of the gravitational forces of the kinematic chain members and members of the excavator drive mechanisms for certain axes of joints O_i, m_z - the mass of the material scooped with the bucket, where it is assumed that the centre of the scooped material mass overlaps with the centre of the bucket mass.

The moment of the gravitational forces of the kinematic chain members and members of the excavator drive mechanisms for certain axes of joints O_i, when the bucket is empty, is determined by the equation (Fig. 2):

$$M_{\text{o}i} = -g\sum_{k=i}^{k=5} m_k \left((\vec{r}_{tk} - \vec{r}_i) \times \vec{j}\right) \cdot \vec{e}_i + M_{\text{o}ci} \ \ \forall i = 3, 4, 5, \tag{14}$$

where: M_{oci} - the moment of the gravitational forces of the excavator drive mechanism members for certain axes of joints O_i (i = 3, 4, 5). The moments of the gravitational forces of the excavator drive mechanism members for certain axes of joints O_i (i=3, 4, 5) are determined by the following equations:

$$M_{\text{o}ci}=\begin{cases}M_{\text{o}c3}=-g\dfrac{n_{c3}m_{c3}}{2}\left((\vec{r}_{\text{A}3}-\vec{r}_3)\times\vec{j}\right)\cdot\vec{e}_3-\\ \quad -g\sum\limits_{k=4}^{k=5}n_{ck}m_{ck}\left((\vec{r}_{ctk}-\vec{r}_3)\times\vec{j}\right)\cdot\vec{e}_3,\ \forall i=3\\ M_{\text{o}c4}=-g\dfrac{n_{c4}m_{c4}}{2}\left((\vec{r}_{\text{A}4}-\vec{r}_4)\times\vec{j}\right)\cdot\vec{e}_4-\\ \quad -g\dfrac{n_{c5}m_{c5}}{2}\left((\vec{r}_{\text{A}5}-\vec{r}_4)\times\vec{j}\right)\cdot\vec{e}_4,\ \forall i=4\\ M_{\text{o}c5}=-g\dfrac{m_{c5}}{2}\left((\vec{r}_{\text{A}5}-\vec{r}_5)\times\vec{j}\right)\cdot\vec{e}_5,\ \forall i=5\end{cases}\tag{15}$$

where: $\vec{r}_{\text{A}3},\vec{r}_{\text{A}4},\vec{r}_{\text{A}5}$ - the coordinates of joints where hydraulic cylinders are connected to the kinematic chain members (Fig. 2).

Depending on the position of the bucket, the mass of the material scooped by the bucket is defined by the expression:

$$m_z=\begin{cases}\rho_z\cdot V\left|\cos\varphi_5\right| & \forall\ 270°<\varphi_5<90°\\ 0 & \forall\ 270°<\varphi_5<90°\end{cases},\tag{16}$$

where: ρ_z - the density of the material, V - the volume of the bucket.

The value of the lateral digging resistance W_b, for a particular position of the excavator kinematic chain, is defined by the equation [18]:

$$W_b=\frac{m\cdot g\cdot L}{4\cdot x_w}\mu_o\tag{17}$$

where: m - the mass of the excavator, L - the length of the continuous tracks footprint (Fig. 2), μ_o - the coefficient of the turning resistance of the tracks against the excavator support surface, x_w - the horizontal coordinate of the bucket cutting edge centre.

3 Bearing loads

The fictive interruption of the kinematic chain of the excavator in the joint O_2 of the 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:

$$\vec{F}_2=\vec{W}-g\sum_{i=2}^{5}m_i\vec{j}-g\sum_{i=3}^{5}m_{ci}\vec{j}-gm_z\vec{j}\tag{18}$$

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

$$\vec{M}_2=((\vec{r}_\text{w}-\vec{r}_2)\times\vec{W})-g\sum_{i=2}^{5}m_i((\vec{r}_{ti}-\vec{r}_2)\times\vec{j})-\\-gm_z((\vec{r}_{t5}-\vec{r}_2)\times\vec{j})-g\sum_{i=3}^{i=5}n_{ci}m_{ci}((\vec{r}_{cti}-\vec{r}_2)\times\vec{j})\tag{19}$$

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

Components of slewing bearing loads of the excavator rotating platform are:

- axial force: $F_{2\text{a}}=F_{2y}$ (20)
- radial force: $F_{2\text{r}}=\left(F_{2x}^2+F_{2z}^2\right)^{0,5}$ (21)
- and moment: $M_{2\text{r}}=\left(M_{2x}^2+M_{2z}^2\right)^{0,5}$ (22)

Moment $M_{2\text{r}}$, whose vector lies in the horizontal plane subjects the slewing bearing to loading, while moment M_{2y}, whose vector direction matches the bearing axis, balances the drive moment of the platform rotation mechanism. The size of the bearing is selected on the basis of the determined equivalent spectrum of bearing loads and diagrams of bearing loading capacity (curves I, II, III, IV, and V, Fig. 4), which are provided by the specialized bearing manufacturers [19].

The equivalent spectrum of bearing loads consists of an equivalent force and an equivalent bearing load moment determined by the equations for:

a) equivalent force F_e:

$$F_\text{e}=\left(a\cdot F_{2\text{a}}+b\cdot F_{2\text{r}}\right)f_\text{s}\tag{23}$$

b) and equivalent moment M_e:

$$M_\text{e}=f_\text{s}\cdot M_{2\text{r}}\tag{24}$$

where: a - the factor of the axial force influence, b - the factor of the radial force influence, f_s - 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.

To satisfy all of the above requirements, on the basis of the previously given calculation procedure, a computer programme was developed to determine the loading spectrum and select the slewing bearing of the platform rotation drive in hydraulic excavators.

During the analysis the following is set at the programme input: L_i - parameters of the members of the excavator kinematic chains, C_i - parameters of the drive mechanisms of the excavator manipulator, p_m - the maximum pressure of the hydraulic static system of the excavator, p_o - the pressure in the retraction duct of the hydraulic static system of the excavator, N_3 - the desired number of the manipulator boom positions in its range of movement, N_4 - the desired number of the stick positions in its range of movement for a certain position of the manipulator boom, N_5 - the desired number of the bucket positions in its range of movement for a certain position of the manipulator stick, N_w - the desired number of changes in the angle θ_w of the directions in which the digging resistance acts for a certain position of the bucket, θ_wp - the initial angle of the direction in which the digging resistance acts, $\theta_{\text{w}k}$ - the final angle of the direction in which the digging resistance acts, ρ_z - the density of the scooped material, V_z - the volume of the bucket, μ_p - the coefficient of adherence, a - the factor of the influence of the slewing bearing force, b - the factor of the influence of the radial bearing force, f_s - the factor of the bearing working conditions.

Based on the input values, and through the cyclic change of the given numbers N_w, N_5, N_4 and N_3 (Fig. 3), the programme determines: a) geometric values (θ_i, r_i, r_{ti}, r_w) which define the position of the joint centres and mass centres of the excavator kinematic chain, b) loading moments (M_{oi} ,M_{ri}) and drive moment (M_{pi}) of drive mechanisms, c) boundary digging resistances (W_o, W_1, W_3, W_4, W_5), for the entire working range of the excavator, d) components of slewing bearing loads (F_{2a}, F_{2r}, M_{2r}), and e) equivalent slewing bearing loads (F_e, M_e).

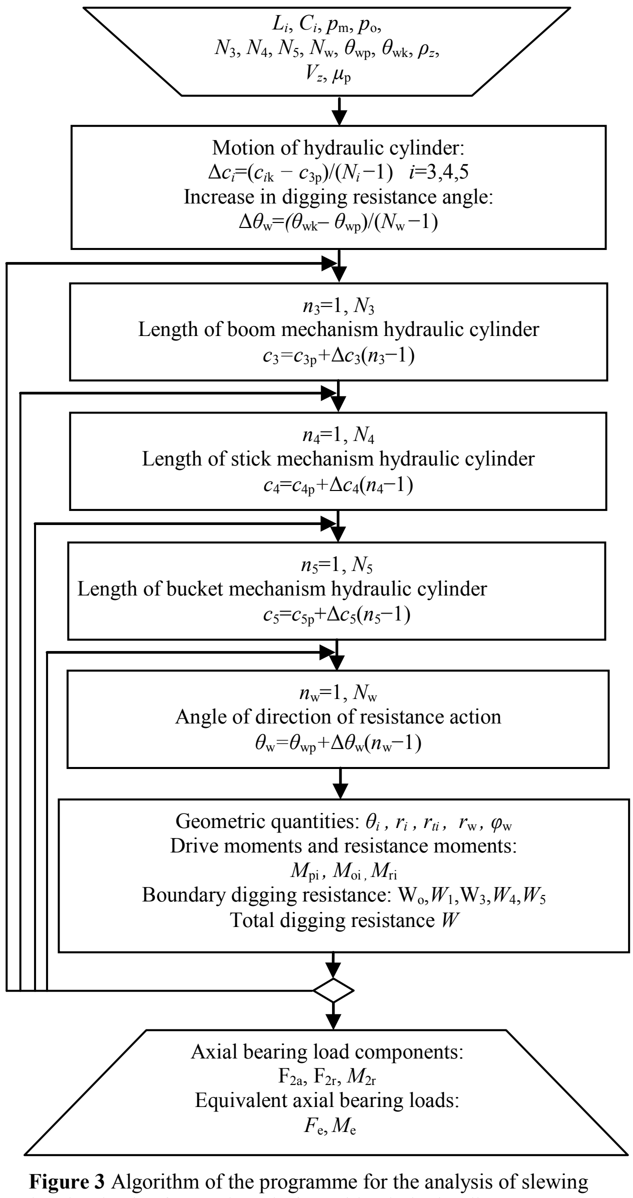

Figure 3 Algorithm of the programme for the analysis of slewing bearing loads of a rotating platform drive in hydraulic excavators

The programme output yields a spectrum of bearing loads for the entire working range of the excavator which consists of equivalent bearing loads for each position of the excavator kinematic chain and for each given direction in which the digging resistance acts.

4 Results and discussion

By using the developed programme, the analysis of slewing bearing loads was performed for a rotating platform of a hydraulic excavator with the mass of 100 000 kg and power of 400 kW with a shovel attachment. The kinematic chain of the selected excavator size could be equipped with two different support and movement mechanisms with continuous tracks and six loading buckets of various volumes for work in different working conditions and excavation of materials with different characteristics.

As an example, the spectrum of slewing bearing loads of a rotating platform drive was determined for potential variants A and B of the excavator kinematic chain.

Variant A of the excavator kinematic chain had a shorter support and movement mechanism with the footprint length of L=4640 mm, track distance of B=3600 mm, and the loading bucket with the volume of V=4,4 m^3 for digging the material with the density of ρ_z=2200 kg/m^3.

Variant B of the excavator kinematic chain had a longer support and movement mechanism with the footprint length of L=5035 mm, track distance of B=3600 mm, and the loading bucket with the volume of V=6,5 m^3 for digging the material with the density of ρ_z=1650 kg/m^3.

The input database of the programme contained parameters (Tab. 1) which were the same for both variant A and B of the excavator kinematic chain.

Table 1 Values of the input parameters of the programme

Parameters	Values	Parameters	Values
p_m	32 MPa	θ_{wp}	200°
p_o	1,5 MPa	θ_{wk}	300°
N_3	30	μ_p	0,85
N_4	20	a	1
N_5	10	b	2,05
N_w	10	f_s	1,45

On the basis of the set input parameters, using the developed programme, the spectrum of slewing bearing loads was determined for the rotating platform rotary drive for variants A and B of the excavator kinematic chain. The programme output provided, among other things, the equivalent force and the equivalent bearing load moment for variants A and B of the excavator kinematic chain, determined for 6000 ($N_3 \times N_4 \times N_5$) positions in the entire working range and in each position for 10 different directions in which potential digging resistances could act. The obtained values of the equivalent forces and moments are shown in the form of a diagram (Fig. 4) as a spectrum of bearing loads for the longitudinal ($x-x$) and transverse ($z-z$) potential rollover lines for variants A and B of the excavator kinematic chain. All of the diagrams of the spectra of slewing bearing loads for variants A and B of the excavator kinematic chain show diagrams of the permitted loading capacity of the five same bearings which differ in size (Fig. 4, curves I, II, III, IV, V) [19]. The diagram of the permitted loading capacity represents the dependency of the allowed slewing bearing moment and force.

The rotating platform drive corresponds to that size of the bearing whose permitted loading capacity is closest yet larger than the potential values of the spectrum of the equivalent bearing loads.

For example, by comparing the spectra of the equivalent bearing loads for variant A of the excavator kinematic chain with the loading capacity diagrams it can be noticed that the potential longitudinal rollover line (x–x) (Fig. 4a) corresponds to the bearing size III, while the transverse rollover line (z–z) (Fig. 4b) corresponds to the bearing size II. As far as variant B of the excavator kinematic chain is concerned, the potential longitudinal rollover line (x–x) (Fig. 4c) corresponds to the bearing size IV, and the transverse rollover line (z–z) (Fig. 4d) corresponds to the bearing size IV.

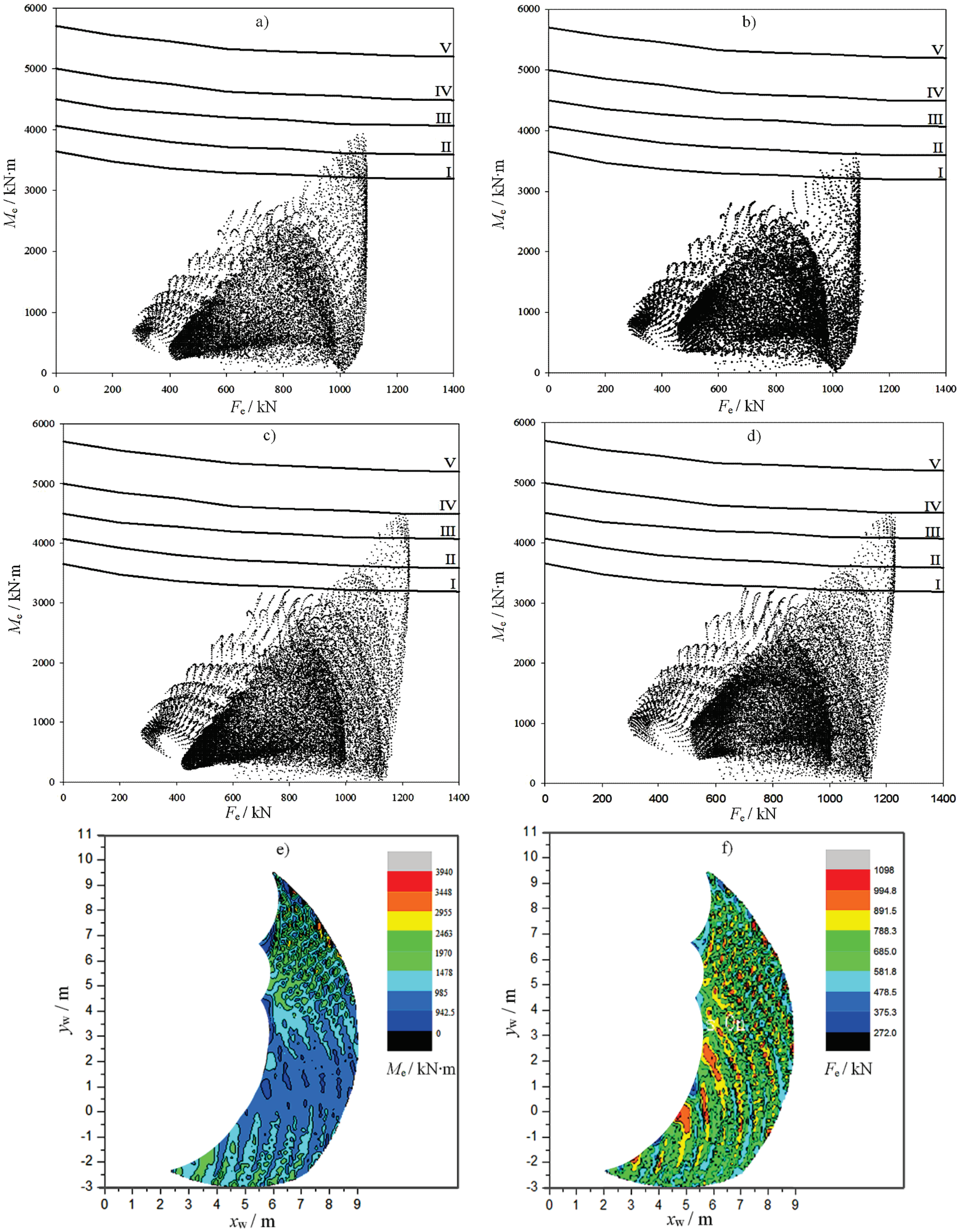

Figure 4 Spectrums of load slewing bearing rotating platform of hydraulic excavators: a) variant A - longitudinal rollover line x–x, b) variant A - transverse rollover line z–z, c) variant B - longitudinal rollover line x–x, d) variant B - transverse rollover line z–z, e) spectrum of equivalent moment - variant A, f) spectrum of equivalent force - variant A

Analysis results can also be presented in the form of a spectrum of equivalent moment (Fig. 4e) and equivalent force (Fig. 4f) depending on the coordinates (x_w, y_w) of the top of the cutting edge of the tool for the entire working range of the excavator. Based on these spectra, one can separate the segments of the working range in which, when the excavator is in action, the slewing bearing of the rotating platform drive has the highest equivalent loads.

5 Conclusion

The synthesis procedure for the rotating platform drive of hydraulic excavators should, among other things, provide for the selection of the slewing bearing size. It is characteristic for all sizes of hydraulic excavators that the same model of excavator can have different configurations of kinematic chains equipped with various working tools. Furthermore, an excavator with the same configuration of the kinematic chain has a number of different positions and working conditions during its operation in its working range. For these reasons, this paper defines a mathematical model upon which software was developed that enables a comprehensive analysis of equivalent slewing bearing loads of an excavator rotating platform which allow for a reliable selection of the bearing size. The comprehensive analysis using the developed software includes the determination of the spectra of equivalent slewing bearing loads for a rotating platform in each possible configuration of the excavator kinematic chain for a desired number of working positions in the entire working range and in every position for a desired number of different working manners and conditions.

The comparative analysis of the obtained results presented in this paper shows that for the same excavator model with a shovel attachment, the slewing bearing loads differ significantly depending on the position and working conditions and the size of the tool – bucket. The final selection of the slewing bearing size requires a detailed analysis of the slewing bearing load for all of the other attachment and tool configurations of the excavator.

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Authors' addresses

Vesna Jovanović, MSc
University of Niš, Faculty of Mechanical Engineering
A. Medvedeva 14, 18000 Niš, Serbia
E-mail: vesna.nikolic@masfak.ni.ac.rs

Dragoslav Janošević, Prof. dr
University of Niš, Faculty of Mechanical Engineering
A. Medvedeva 14, 18000 Niš, Serbia
E-mail: janos@masfak.ni.ac.rs

Nikola Petrović, MSc
University of Niš, Faculty of Mechanical Engineering
A. Medvedeva 14, 18000 Niš, Serbia
E-mail: petrovic.nikola@masfak.ni.ac.rs