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

Vesna Jovanović, Dragoslav Janošević, Nikola Petrović

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

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 L1 (Fig. 1b,c), rotating platform L2, and changeable multi-member manipulators Lm, 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 forward 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 L2 (Fig. 1b,c), which is attached to the support and movement mechanism L1 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 motor 1 (Fig. 1d), a reducer 2 coupled over an output gear drive mechanism of the platform consists of a hydraulic fifth class, in the form of a slewing bearing. The rotating L2, and changeable multi-member manipulators Lm, which

![Figure 1 Hydraulic excavators: a) working tools, b) with backhoe attachment](image-url)
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 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 shovelling 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 \( O_i \) 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]:

\[
L_i = \{ \tilde{e}_i, \tilde{s}_i, \tilde{t}_i, m_i \} \quad \forall i = 1, 2, 3, 4, 5,
\]

where: \( \tilde{e}_i = \{ e_{ix}, e_{iy}, e_{iz} \} \) - the unit vector of joint \( O_i \) axis which connects member \( L_i \) to the previous member \( L_{i-1} \), \( \tilde{s}_i = \{ s_{ix}, s_{iy}, s_{iz} \} \) - 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), \( \tilde{t}_i = \{ t_{ix}, t_{iy}, t_{iz} \} \) - 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 \( c_5, c_6 \) and \( c_3 \) as actuators (Fig. 2).

Each drive mechanism \( C_i \) of the excavator manipulator is determined using a set of quantities:

\[
C_i = \{ d_{i1}, d_{i2}, c_{i3}, c_{i4}, \tilde{a}_i, \tilde{b}_i, m_{ei}, n_{ei} \} \quad \forall i = 3, 4, 5, \tag{2}
\]

where: \( d_{i1}, d_{i2} \) - the diameter of the piston and piston rod of the hydraulic cylinder, \( c_{i3} c_{i4} \) - the initial and final length of the hydraulic cylinder, \( \tilde{a}_i, \tilde{b}_i \) - the vectors of the position of joint centres where the hydraulic cylinder is connected to the kinematic chain members, \( m_{ei} \) the mass of the hydraulic cylinder, \( n_{ei} \) - the number of hydraulic cylinders of the drive mechanism.

The digging resistance vector is determined with the equation:

\[
\vec{\bar{W}} = W_r \cos \varphi_w \vec{\tilde{t}} + W_r \sin \varphi_w \vec{\tilde{j}} + W_5 \vec{\tilde{k}}, \tag{3}
\]

where: \( W_r \) - the digging resistance which acts in the plane of the manipulator, \( W_5 \) - the lateral digging resistance, \( \varphi_w \) - 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:

\[
\varphi_w = \sum_{i=3}^{5} \theta_i + \theta_w, \tag{4}
\]

where: \( \theta_i (i=3, 4, 5) \) - 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, $\theta_w$ - the angle of the direction in which the digging resistance acts in relation to the positive $O_x$ 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](image)

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

$$W_r = \min\{W_o, W_1, W_3, W_4, W_5\},$$  \hfill (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 $W_r$:

$$\mathbf{r}W_r = \cos\varphi_w \mathbf{i} + \sin\varphi_w \mathbf{j}. \hfill (6)$$

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:

$$W_o = \frac{mg \cdot \mu_p}{\cos\varphi_w}, \hfill (7)$$

where: $m$ - the total mass of the excavator, $\mu_p$ - 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 $\mathbf{r}W_r$, 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):

$$O_1O_2 = \overline{\delta}_1 \quad O_2O_3 = \overline{\delta}_2 \quad O_3O_4 = \overline{\delta}_3 \quad O_4O_5 = \overline{\delta}_4 \quad O_5O_w = \overline{\delta}_5$$

where:

- $\overline{\delta}_1, \overline{\delta}_2, \overline{\delta}_3, \overline{\delta}_4, \overline{\delta}_5$ - are the potential 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 vector of the position of the hydraulic cylinder: $W_i = \frac{-M_{oi} \times \text{ort} W_i}{(\vec{r}_u - \vec{r}_i) \times \text{ort} W_i} \cdot \hat{e}_i$,
\[ W_1 = \begin{cases} \begin{aligned} \vec{r}_u &> 0, \ \phi_2 > \phi_0 > (\phi_1 + 180^\circ), \\
\vec{r}_u &< 0, \ \phi_1 > \phi_0 > (\phi_2 + 180^\circ), \\
\vec{r}_u &< 0, \ \phi_1 = 180^\circ > \phi_0 > \phi_2, \\
\vec{r}_u &> 0, \ \phi_2 = 180^\circ > \phi_0 > \phi_1. \end{aligned} \end{cases} \]
\[ W_{12} = \begin{cases} \begin{aligned} \vec{r}_u &> 0, \ \phi_2 > \phi_0 > (\phi_1 + 180^\circ), \\
\vec{r}_u &< 0, \ \phi_1 > \phi_0 > (\phi_2 + 180^\circ), \end{aligned} \end{cases} \]

where: $\vec{e}_i = [0,0,1]^T$ - the unit vector of the first joint vector (for the longitudinal $x$-axis) or transverse $z$-axis excavator rollover line, $M_{oi}$ - the gravitational moments for potential excavator rollover lines, i.e., joint joints $O_{i1}$, $O_{i2}$, $\vec{r}_u$ - the position of the bucket cutting edge, $\vec{r}_{i1}$, $\vec{r}_{i2}$ - the vectors of the position of the centre of the appropriate first joint $O_{i1}$, $O_{i2}$, $\vec{r}_u$ - the vertical coordinate of the bucket top, $\phi_{11}$, $\phi_{12}$ - the angles of the position of vectors $(\vec{r}_u - \vec{r}_i)$ and $(\vec{r}_u - \vec{r}_{i2})$ in relation to the horizontal plane $OAX$, determined by the equations:

$$\phi_{11} = \arccos \left( \frac{\vec{r}_u - \vec{r}_{i1}}{\vec{r}_u - \vec{r}_{i1}} \right), \quad \phi_{12} = \arccos \left( \frac{\vec{r}_u - \vec{r}_{i2}}{\vec{r}_u - \vec{r}_{i2}} \right)$$

The gravitational moments for potential excavator rollover lines, i.e., joint joints $O_{i1}$, $O_{i2}$:

$$M_{o1} = \begin{cases} \begin{aligned} M_{o11} &= \sum_{k=1}^{i} \sum_{k=1}^{i} m_k (\vec{r}_{ik} - \vec{r}_{i1}) \times \hat{e}_i - \\
M_{o12} &= \sum_{k=1}^{i} \sum_{k=1}^{i} m_k (\vec{r}_{ik} - \vec{r}_{i2}) \times \hat{e}_i \\
M_{o13} &= \sum_{k=1}^{i} \sum_{k=1}^{i} m_k (\vec{r}_{ik} - \vec{r}_{i3}) \times \hat{e}_i - \\
M_{o14} &= \sum_{k=1}^{i} \sum_{k=1}^{i} m_k (\vec{r}_{ik} - \vec{r}_{i4}) \times \hat{e}_i - \\
M_{o15} &= \sum_{k=1}^{i} \sum_{k=1}^{i} m_k (\vec{r}_{ik} - \vec{r}_{i5}) \times \hat{e}_i. \end{aligned} \end{cases}$$

where: $m_k$ - the mass of the kinematic chain members, $m_{ck}$ - the mass of the hydraulic cylinders, $\vec{r}_{ik}$ - the vector of the position of the kinematic chain member mass centre, $\vec{r}_{ck}$ - 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 $\text{ort} W_i$ and the position of the excavator kinematic chain upon the action of the maximum drive moments $M_{oi}$ are determined from the balance conditions for the manipulator joints $O_i$ axes (Fig. 2):

$$W_i = \begin{cases} \begin{aligned} \vec{r}_u &> 0, \ \phi_2 > \phi_0 > (\phi_1 + 180^\circ), \\
\vec{r}_u &< 0, \ \phi_1 > \phi_0 > (\phi_2 + 180^\circ), \\
\vec{r}_u &< 0, \ \phi_1 = 180^\circ > \phi_0 > \phi_2, \\
\vec{r}_u &> 0, \ \phi_2 = 180^\circ > \phi_0 > \phi_1. \end{aligned} \end{cases} \]

where: $M_{oi}$ - the maximum drive moments of manipulator mechanisms for both directions in which they act (upon piston pushing and piston pulling in the hydraulic cylinder), $M_{oi}$ - the moment of gravitational forces of the kinematic chain members, members of the excavator drive mechanisms, and the mass of soil scooped by the 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, $\vec{e}_i = [0,0,1]^T$ - the unit vector of the joint axes in the manipulator kinematic chain.

The moment of gravitational forces of manipulator mechanisms for both directions in which they act (upon piston pushing and piston pulling in the hydraulic cylinder):

$$M_{oi} = \begin{cases} \begin{aligned} M_{oi1} &= \text{sgn}(\hat{e}_i) \eta_{ci} \left[ \frac{d_i^2 \pi}{4} p_m - \frac{d_i^2 \pi}{4} p_0 \right] \eta_{ci}, \\
M_{oi2} &= \text{sgn}(\hat{e}_i) \eta_{ci} \left[ \frac{d_i^2 \pi}{4} p_m - \frac{d_i^2 \pi}{4} p_0 \right] \eta_{ci}, \end{aligned} \end{cases}$$

where: $\hat{e}_i$ - 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 piston pressure during the extension stroke of the hydraulic cylinder, $p_0$ - the maximum piston pressure during the retraction stroke of the hydraulic cylinder, $\eta_{ci}$ - 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 bucket, for certain axes of joints $O_i$ is determined by the equation:

$$M_{oi} = M_{oi} - g_m \left( \vec{r}_{i5} - \vec{r}_i \right) \times \hat{e}_i, \quad \forall i = 1, 3, 4, 5,$$

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 $O_i$, $m_i$ - 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):

$$M_{oi} = \sum_{k=1}^{i} \sum_{k=1}^{i} m_k (\vec{r}_{ik} - \vec{r}_i) \times \hat{e}_i + M_{oi1}, \quad \forall i = 1, 3, 4, 5,$$

where: $M_{oi1}$ - 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 $O_i$ are determined by the following equations:
\[ M_{oc3} = -g \frac{n_3 m_3}{2} \left( (\vec{r}_{A3} - \vec{r}_i) \times \vec{j} \right) \vec{e}_3 - \sum_{k=4}^{5} n_{ik} m_{ik} \left( (\vec{r}_{ik} - \vec{r}_3) \times \vec{j} \right) \vec{e}_3, \quad \forall t = 3 \]

\[ M_{oc4} = -g \frac{n_4 m_4}{2} \left( (\vec{r}_{A4} - \vec{r}_i) \times \vec{j} \right) \vec{e}_4 - \sum_{i=2}^{4} n_{i} m_{i} \left( (\vec{r}_{Ai} - \vec{r}_3) \times \vec{j} \right) \vec{e}_4, \quad \forall i = 4 \]

\[ M_{oc5} = -g \frac{n_5 m_5}{2} \left( (\vec{r}_{A5} - \vec{r}_3) \times \vec{j} \right) \vec{e}_5, \quad \forall t = 5 \]

where: \( \vec{r}_{A3}, \vec{r}_{A4}, \vec{r}_{A5} \) - 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:

\[ m_z = \begin{cases} \rho_z V \cos \phi_3 & \forall 270^\circ < \phi_3 < 90^\circ \\ 0 & \forall 270^\circ < \phi_3 < 90^\circ \end{cases} \]

where: \( \rho_z \) - 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]:

\[ W_b = \frac{m \cdot g \cdot L}{4 \cdot x_u} \mu_o \]

where: \( m \) - the mass of the excavator, \( L \) - the length of the continuous tracks footprint (Fig. 2), \( \mu_o \) - the coefficient of the turning resistance of the tracks against the excavator support surface, \( x_u \) - 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:

\[ \vec{F}_2 = \vec{W} - g \sum_{j=2}^{5} m_j \vec{j} - g \sum_{i=3}^{5} m_{i} \vec{j} - g m_z \vec{j} \]

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

\[ \vec{M}_2 = ((\vec{W} - \vec{r}_2) \times \vec{W}) - g \sum_{j=2}^{5} m_j ((\vec{r}_j - \vec{r}_2) \times \vec{j}) - \sum_{i=3}^{5} m_{i} m_{i} ((\vec{r}_{i} - \vec{r}_2) \times \vec{j}) - g m_z ((\vec{r}_{15} - \vec{r}_2) \times \vec{j}) - g \sum_{i=3}^{5} n_{i} m_{i} ((\vec{r}_{i} - \vec{r}_2) \times \vec{j}) \]

where: \( \vec{r}_i \) - 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: \( F_{2a} = F_{2y} \)
- radial force: \( F_{2r} = (F_{2x}^2 + F_{2z}^2)^{0.5} \)
- and moment: \( M_{2r} = (M_{2x}^2 + M_{2z}^2)^{0.5} \)

Moments \( M_{2r} \), whose vector lies in the horizontal plane subjects the slewing bearing to loading, while moment \( M_{2r} \), 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 \( F_e \):

\[ F_e = (a \cdot F_{2a} + b \cdot F_{2r}) \]

b) and equivalent moment \( M_e \):

\[ M_e = f_s \cdot M_{2r} \]

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, \( p_{ru} \) - the pressure in the retraction duct of the hydraulic static system of the excavator, \( N_1 \) - the desired number of the manipulator boom positions in its range of movement, \( N_2 \) - the desired number of the stick positions in its range of movement for a certain position of the manipulator boom, \( N_3 \) - the desired number of the bucket positions in its range of movement for a certain position of the manipulator stick, \( N_4 \) - the desired number of changes in the angle \( \theta_{h} \) of the directions in which the digging resistance acts for a certain position of the bucket, \( \theta_{h1} \) - the initial angle of the direction in which the digging resistance acts, \( \theta_{h2} \) - the final angle of the direction in which the digging resistance acts, \( p_s \) - the density of the scooped material, \( V_b \) - the volume of the bucket, \( \mu_o \) - 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 \( N_s, N_b, N_c \) and \( N_k \) (Fig. 3), the programme determines: a) geometric values \( \theta, r, r_n, r_w \) which define the position of the joint centres and mass centres of the excavator kinematic chain, b) loading moments \( (M_a, M_d) \) and drive moment \( (M_{p_a}) \) of drive mechanisms, c) boundary digging resistances \( (W_{w_1}, W_{s_1}, W_{d_1}, W_{f_1}) \), for the entire working range of the excavator, d) components of slewing bearing loads \( (F_{2a}, F_{2b}, M_{2a}) \), and e) equivalent slewing bearing loads \( (F_c, M_c) \).

Motion of hydraulic cylinder: 
\[
\Delta c_i = (c_{ai} - c_{pi})(N_i - 1)
\]
Increase in digging resistance angle: 
\[
\Delta \theta_w = \theta_{w_1} - \theta_{w_2} = \theta_{w_i} - \theta_{w_i+1}
\]

Length of boom mechanism hydraulic cylinder
\[
c_i = c_{pi} + \Delta c_i(n_i - 1)
\]
Length of stick mechanism hydraulic cylinder
\[
c_i = c_{pi} + \Delta c_i(n_i - 1)
\]
Length of bucket mechanism hydraulic cylinder
\[
c_i = c_{pi} + \Delta c_i(n_i - 1)
\]
Angle of direction of resistance action
\[
\theta_w = \theta_{w_1} + \Delta \theta_w(n_i - 1)
\]

Geometric quantities: \( \theta, r_c, r_s, r_w, r_b \)
Drive moments and resistance moments: 
\( M_a, M_d, M_{p_a} \)
Boundary digging resistance: \( W_{w_1}, W_{s_1}, W_{d_1}, W_{f_1} \)
Total digging resistance \( W \)

Axial bearing load components: 
\( F_{2a}, F_{2b}, M_{2a} \)
Equivalent axial bearing loads: 
\( F_c, M_c \)

**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 work 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 \( \rho_w = 2200 \) 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 \( \rho_w = 1650 \) 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>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_m )</td>
<td>32 MPa</td>
<td>( \theta_{w_1} )</td>
<td>200°</td>
</tr>
<tr>
<td>( p_a )</td>
<td>1,5 MPa</td>
<td>( \theta_{w_2} )</td>
<td>300°</td>
</tr>
<tr>
<td>( N_1 )</td>
<td>30</td>
<td>( \mu_1 )</td>
<td>0,85</td>
</tr>
<tr>
<td>( N_2 )</td>
<td>20</td>
<td>( a )</td>
<td>1</td>
</tr>
<tr>
<td>( N_3 )</td>
<td>10</td>
<td>( b )</td>
<td>2,05</td>
</tr>
<tr>
<td>( N_w )</td>
<td>10</td>
<td>( f_s )</td>
<td>1,45</td>
</tr>
</tbody>
</table>

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 \( (N_3> N_4> N_2) \) 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 \((\mathbf{x}-\mathbf{x})\) (Fig. 4a) corresponds to the bearing size III, while the transverse rollover line \((\mathbf{z}-\mathbf{z})\) (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 \((\mathbf{x}-\mathbf{x})\) (Fig. 4c) corresponds to the bearing size IV, and the transverse rollover line \((\mathbf{z}-\mathbf{z})\) (Fig. 4d) corresponds to the bearing size IV.

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.

Acknowledgement

The paper was done within the project TR 35049 financed by the Ministry of Education and Science of the Republic of Serbia.

6 References


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

Dragosлав Janoшевић, 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