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Spectra of slewing bearing load of a rotating-platform drive in hydraulic excavators

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Abstract. The paper presents a mathematical model for the determination of spectra of equivalent slewing bearing loads of a rotating platform drive in hydraulic excavators with a backhoe attachment. The spectrum of equivalent bearing loads is defined on the basis of possible digging resistances which represent the minimal value from a set of boundary digging resistances that enable the stability of the excavator and boundary digging resistances which can be overcome by the excavator drive mechanisms. The same models of the excavator can have different variants of the kinematic chain which can occupy a number of different positions and working conditions. Hence, based on the general mathematical model a software was developed for a detailed analysis of the slewing bearing load of a rotating platform drive for a desired number of positions in the entire working range of the excavator for every possible variant of the kinematic chain.

1. Introduction

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 (Figure 1(b) and (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 and hooks (Figure 1(a)). 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 (Figure 1(b)). For digging operations above the ground level the away from oneself technology and a shovel attachment are used (Figure 1(c)). Hydraulic excavators perform spatial manipulation using the rotating platform, L_2 (Figure 1(b) and (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 (Figure 1(d)), a reducer coupled over an output gear with a ring gear of a slewing bearing. Generally, a slewing bearing (Figure 1(d)) consists of an inner ring gear, which is bolted to the support and movement mechanism, L_1, and a toothless outer ring, which is bolted to the rotating platform, L_2. Rolling elements (balls and 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;

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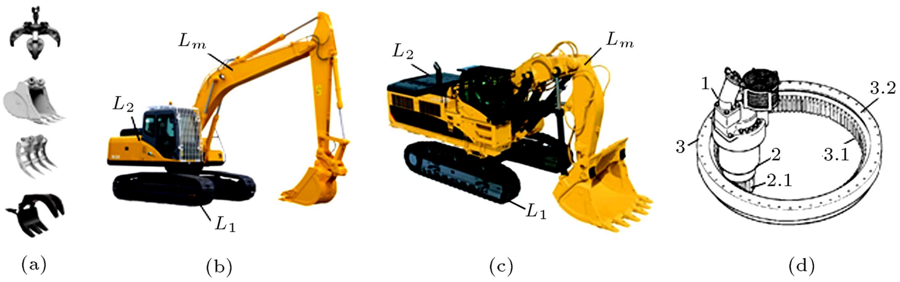

Figure 1. Hydraulic excavators: (a) Working tools; (b) with backhoe attachment; (c) with shovel attachment; and (d) drive mechanism of a hydraulic excavator rotating platform.

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 mobile machine analysis [3-5];
c) Development of drive mechanisms and control systems [6-9];
d) Definition of indicators for analysis and evaluation of excavator digging efficiency [10].

Research into rotating drive mechanisms of excavator platforms deal with:

a) Loads of slewing bearing rolling elements [11,12];
b) Analysis of slewing bearing loads in excavators with excavating manipulators [13];
c) Regulation of angular velocity of a rotating platform [14-16].

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

2. Mathematical model of the excavator

The mathematical model of the excavator comprises the model of the kinematic chain and the mathematical models of excavator drive mechanisms. The mathematical model encompasses a five-member configuration of the excavator kinematic chain comprising: support and movement mechanism, L_1 (Figure 1), rotating platform, L_2, 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 the 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 plane 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.

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:

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

where $\widehat{\vec{e}}_i$ is the unit vector of joint O_i axis which connects member, L_i, to the previous member L_{i-1}, $\widehat{\vec{s}}_i$ is the position vector of the 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), $\widehat{\vec{t}}_i$ is the position vector of the member mass centre, and m_i is 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 (Figure 2). Each drive mechanism, C_i, of the excavator manipulator is determined using a set of quantities:

$$C_i = \left\{ d_{i1}, d_{i2}, c_{ip}, c_{ik}, \widehat{\vec{a}}_i, \widehat{\vec{b}}_i, m_{ci}, n_{ci} \right\}$$

$$\forall\ i = 3, 4, 5, \tag{2}$$

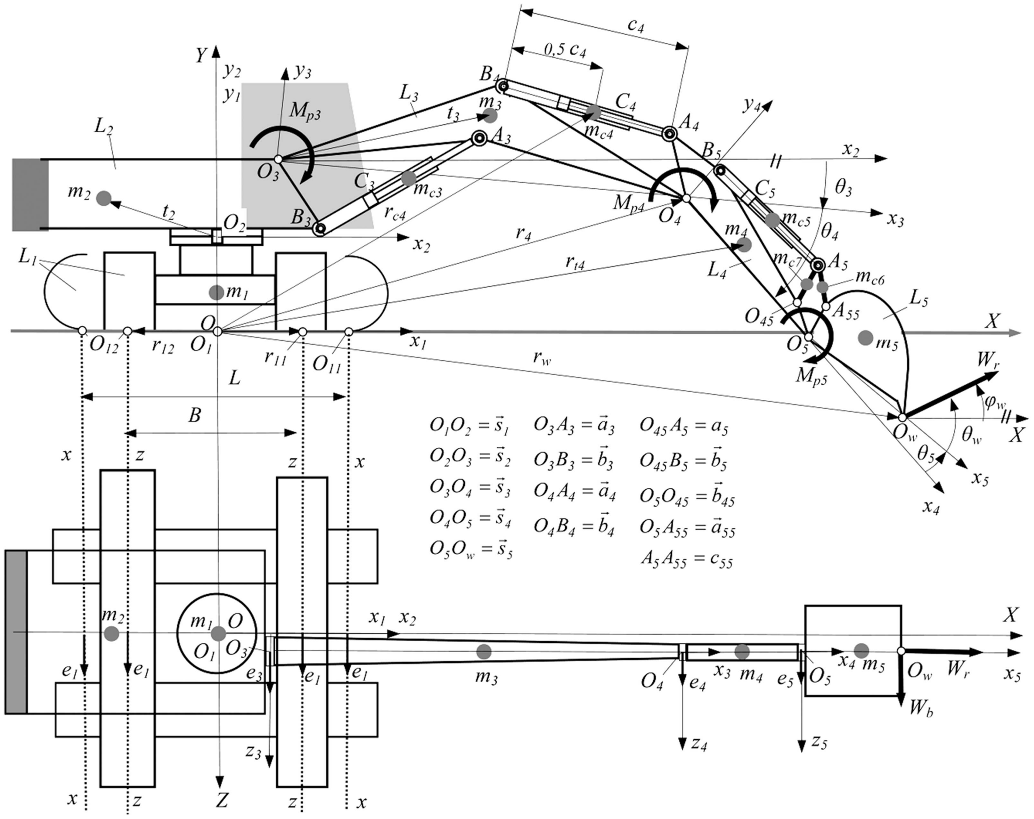

Figure 2. Determining the load of slewing bearing and slewing platforms of hydraulic excavator with a backhoe attachment.

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

The subset of transmission parameters of the drive mechanism of the bucket C_5 is determined by the set:

$$C_{p5} = \left\{ a_5, c_{55}, \overset{\frown}{\vec{a}}_{55}, \overset{\frown}{\vec{b}}_{45}, m_{c6}, m_{c7} \right\}, \tag{3}$$

where a_5 is the length of the lever of the bucket cylinder in the transmission part of the drive mechanism (Figure 2); c_{55} is the length of the link in the transmission part of the drive mechanism, $\overset{\frown}{\vec{a}}_{55}$ and $\overset{\frown}{\vec{b}}_{45}$ are the coordinates of the position of the centre of joints in which transmission levers are connected to the links; m_{c6} is the mass of the link in the transmission part of the drive mechanism; and m_{c7} is the mass of the lever of the bucket cylinder in the transmission part of the drive mechanism.

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 surfaces represents a polygon bounded by potential longitudinal x-x (Figure 2) and transverse z-z excavator rollover lines. Inside the polygon, the first joint has the shape of a translatory - sliding joint, while on the edges of the polygon it has the shape of rotary joints, O_{11} and 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; 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.

The digging resistance vector is determined with the equation:

$$\vec{W} = W_r \cos\varphi_w \vec{i} + W_r \sin\varphi_w \vec{j} + W_b \vec{k}, \tag{4}$$

where W_r is the digging resistance which acts in the plane of the manipulator; W_b is the lateral digging resistance; and 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:

$$\varphi_i = \sum_{3}^{i} \theta_i + \theta_w, \tag{5}$$

where θ_i ($i = 3, 4, 5$) is the angle of the relative position of member, L_i, related to L_{i-1} (upon the rotation around the axis of joint, O_i, by changing the length, c_i, of the hydraulic drive), θ_w is 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.

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

$$W_r = \min\left\{W_o, W_1, W_3, W_4, W_5\right\}, \tag{6}$$

where W_o is the highest boundary digging resistance determined from the excavator non-sliding conditions in the plane of the support surface; W_1 is the highest boundary digging resistance determined from the given excavator stability conditions for potential rollover lines; and W_3, W_4, and 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, is:

$$\text{ort}\vec{W}_r = \cos\varphi_w \vec{i} + \sin\varphi_w \vec{j}. \tag{7}$$

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:

$$W_o = \frac{mg.\mu_p}{|\cos\varphi_w|}, \tag{8}$$

where m is the total mass of the excavator; and μ_p is 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 $\text{ort}\vec{W}_r$, 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} and O_{12}, whose axes represent the potential excavator rollover lines (Figure 2):

$$W_1 = \begin{cases} W_{11} = \frac{-M_{o11}}{\left(\left(\vec{r}_w - \vec{r}_{11} \times \text{ort}\vec{W}_r\right).\vec{e}_1\right)}, \\ \quad \forall\, y_w > 0, \quad \varphi_{12} > \varphi_w > (\varphi_{11} + 180^\circ), \\ \quad \forall\, y_w < 0, \quad \varphi_{11} > \varphi_w > (\varphi_{12} + 180^\circ), \\ W_{12} = \frac{-M_{o12}}{\left(\left(\vec{r}_w - \vec{r}_{12} \times \text{ort}\vec{W}_r\right).\vec{e}_1\right)}, \\ \quad \forall\, y_w > 0 (\varphi_{12} + 180^\circ) > \varphi_w > \phi_{11}, \\ \quad \forall\, y_w < 0 (\varphi_{11} - 180^\circ) > \varphi_w > \phi_{12}, \end{cases} \tag{9}$$

where $\vec{e}_1 = \{0, 0, 1\}$ is the unit vector of the first rotary joint (for the longitudinal x-x or transverse z-z excavator rollover line); M_{o11} and M_{o12} are the gravitational moments for potential excavator rollover lines, i.e. rotary joints, O_{11} and O_{12}; $\vec{r}_w$ is the position vector of the bucket cutting edge centre; $\vec{r}_{11}$ and $\vec{r}_{12}$ are the position vectors of the centre of the appropriate first rotary joint, O_{11} and O_{12}; y_w is the vertical coordinate of the bucket top; and φ_{11} and φ_{12} are the angles of the vectors $(\vec{r}_w - \vec{r}_{11})$ and $(\vec{r}_w - \vec{r}_{12})$ in relation to the horizontal plane OXZ, determined by the equations:

$$\varphi_{11} = \arccos\left(\frac{(\vec{r}_w - \vec{r}_{11}).\vec{i}}{|\vec{r}_w - \vec{r}_{11}|}\right),$$

$$\varphi_{12} = \arccos\left(\frac{(\vec{r}_w - \vec{r}_{12}).\vec{i}}{|\vec{r}_w - \vec{r}_{12}|}\right). \tag{10}$$

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

$$M_{o1} = \begin{cases} M_{o11} = -g\sum_{k=1}^{k=5} m_k \left((\vec{r}_{tk} - \vec{r}_{11}) \times \vec{j}\right).\vec{e}_1 \\ \qquad - g\sum_{k=3}^{k=7} m_{ck} \left((\vec{r}_{ctk} - \vec{r}_{11}) \times \vec{j}\right).\vec{e}_1, \\ M_{o12} = -g\sum_{k=1}^{k=5} m_k \left((\vec{r}_{tk} - \vec{r}_{12}) \times \vec{j}\right).\vec{e}_1 \\ \qquad - g\sum_{k=3}^{k=7} m_{ck} \left((\vec{r}_{ctk} - \vec{r}_{12}) \times \vec{j}\right).\vec{e}_1, \end{cases} \tag{11}$$

where m_k is the mass of the kinematic chain members;

m_{ck} is the mass of the drive mechanism members; $\vec{r}_{tk}$ is the position vector of the centre of mass of the kinematic chain members; and $\vec{r}_{ctk}$ is the position vector of the centre of mass of the drive mechanism members.

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

$$W_i = \frac{-M_{pi} - M_{ri}}{\left((\vec{r}_w - \vec{r}_i) \times \text{ort}\vec{W}_r\right).\vec{e}_i} \qquad \forall\ i = 3,4,5, \quad (12)$$

where M_{pi} is 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} is 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; $\vec{r}_i$ is the position vector of the joint centre in the excavator kinematic chain; and $\vec{e}_i = \{0,0,1\}$ is 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) are:

$$M_{pi} = \begin{cases} M_{pi1} = \text{sign}\left(\dot{\theta}_i\right).r_{ci}.n_{ci} \\ \qquad .\left[\frac{d_{i1}^2\pi}{4}p_m - \frac{\left(d_{i1}^2 - d_{i2}^2\right)\pi}{4}p_o\right].\eta_{ci} \\ \quad \forall\ i = 3,4,5;\ \dot{\theta}_3 > 0,\ \dot{\theta}_4 < 0,\ \dot{\theta}_5 > 0 \\ M_{pi2} = \text{sign}\left(\dot{\theta}_i\right).r_{ci}.n_{ci} \\ \qquad .\left[\frac{\left(d_{i1}^2 - d_{i2}^2\right)\pi}{4}p_m - \frac{d_{i1}^2\pi}{4}p_o\right].\eta_{ci} \\ \quad \forall\ i = 3,4,5;\ \dot{\theta}_3 < 0,\ \dot{\theta}_4 > 0,\ \dot{\theta}_5 < 0, \end{cases} \quad (13)$$

where $\dot{\theta}_i$ is the angular velocities of the kinematic chain members; r_{ci} is 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; p_m is the maximum pressure in the extension line of the hydraulic cylinder; p_o is the maximum pressure in the retraction line of the hydraulic cylinder; and η_{ci} is 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, are determined by the equation:

$$M_{ri} = M_{oi} - gm_z\left((\vec{r}_{t5} - \vec{r}_i) \times \vec{j}\right).\vec{e}_i$$

$$\forall\ i = 1,3,4,5, \quad (14)$$

where M_{oi} is 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 is 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 (Figure 2), is determined by the equation:

$$M_{oi} = -g\sum_{k=i}^{k=5} m_k\left((\vec{r}_{tk} - \vec{r}_i) \times \vec{j}\right).\vec{e}_i + M_{oci}$$

$$\forall\ i = 3,4,5, \quad (15)$$

where M_{oci} is 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:

$$M_{oci} = \begin{cases} M_{oc3} = -g\frac{n_{c3}m_{c3}}{2}\left((\vec{r}_{A3} - \vec{r}_3) \times \vec{j}\right).\vec{e}_3 \\ \qquad -g\sum_{k=4}^{k=7} n_{ck}m_{ck}\left((\vec{r}_{ctk} - \vec{r}_3) \times \vec{j}\right).\vec{e}_3 \\ \quad \forall\ i = 3 \\ M_{oc4} = -g\frac{n_{c4}m_{c4}}{2}\left((\vec{r}_{A4} - \vec{r}_4) \times \vec{j}\right).\vec{e}_4 \\ \qquad -g\sum_{k=5}^{k=7} n_{ck}m_{ck}\left((\vec{r}_{ctk} - \vec{r}_4) \times \vec{j}\right).\vec{e}_4 \\ \quad \forall\ i = 4 \\ M_{oc5} = -g\frac{m_{c6}}{2}\left((\vec{r}_{A5} - \vec{r}_5) \times \vec{j}\right).\vec{e}_5 \\ \quad \forall\ i = 5 \end{cases} \quad (16)$$

where $\vec{r}_{A3}$, $\vec{r}_{A4}$ and $\vec{r}_{A5}$ are the coordinates of joints where hydraulic cylinders are connected to the kinematic chain members (Figure 2).

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

$$m_z = \begin{cases} \rho_z.V.\left|\cos\varphi_5\right| & \forall\ 270^\circ \geq \varphi_5 \geq 90^\circ \\ 0 & \forall\ 270^\circ < \varphi_5 < 90^\circ \end{cases} \tag{17}$$

where ρ_z is the density of the material and V is 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:

$$W_b = \frac{m.g.L}{4.x_w}\mu_o, \tag{18}$$

where m is the mass of the excavator, L is the length of the continuous tracks footprint (Figure 2), μ_o is the coefficient of the turning resistance of the tracks against the excavator support surface, and x_w is 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 yields to:

- The resulting force which subjects the slewing bearing to loading:

$$\vec{F}_2 = \vec{W} - g\sum_{i=2}^{5} m_i\vec{j} - g\sum_{i=3}^{7} m_{ci}\vec{j} - gm_z\vec{j}. \tag{19}$$

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

$$\vec{M}_2 = \left((\vec{r}_w - \vec{r}_2)\times\vec{W}\right) - g\sum_{i=2}^{5} m_i\left((\vec{r}_{ti} - \vec{r}_2)\times\vec{j}\right)$$
$$- gm_z\left((\vec{r}_{t5} - \vec{r}_2)\times\vec{j}\right)$$
$$- g\sum_{i=3}^{i=7} n_{ci}m_{ci}\left((\vec{r}_{cti} - \vec{r}_2)\times\vec{j}\right), \tag{20}$$

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

The components of the force F_2 acting upon joint O_2 along the coordinate axes are:

$$F_{2x} = \vec{F}_2.\vec{i} + \frac{2M_{2y}}{D_{21} - D_{22}}, \qquad F_{2y} = \vec{F}_2.\vec{j},$$
$$F_{2z} = \vec{F}_2.\vec{k}, \tag{21}$$

where D_{21} is the pitch diameter of the interior toothed axial bearing head, and D_{22} is the pitch diameter of the gear at the exit shaft of the platform drive reducer.

The components of moment M_2 of joint O_2 along the coordinate axes are:

$$M_{2x} = \vec{M}_2.\overleftarrow{i}, \qquad M_{2y} = \vec{M}_2.\vec{j}, \qquad M_{2z} = \vec{M}_2.\vec{k}. \tag{22}$$

The components of slewing bearing loads of the excavator rotating platform are:

- Axial force:

$$F_{2a} = F_{2y}. \tag{23}$$

- Radial force:

$$F_{2r} = \left(F_{2x}^2 + F_{2z}^2\right)^{0,5}. \tag{24}$$

- Moment:

$$M_{2r} = \left(M_{2x}^2 + M_{2z}^2\right)^{0,5}. \tag{25}$$

Moment M_{2r}, whose vector lies in the horizontal plane, subjects the slewing bearing to loading, while moment M_2, 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 in Figure 4), which are provided by the specialized bearing manufacturers [17]. 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:

$$F_e = (a.F_{2a} + b.F_{2r})\,f_s. \tag{26}$$

b) Equivalent moment M_e:

$$M_e = f_s.M_{2r}, \tag{27}$$

where a is the factor of the axial force influence, b is the factor of the radial force influence; and f_s is the factor of the bearing working conditions. Values of factors a, b and 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.

4. Selection of bearings

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. To satisfy all of the above requirements, on the basis of the previously given calculation procedure, a computer program 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 program input: L_i are the parameters of the members of the excavator kinematic chains; C_i are the parameters of the drive mechanisms of the excavator manipulator; p_m is the maximum pressure of the hydraulic system of the excavator; p_o is the pressure in the retraction duct of the hydraulic system of the excavator; N_3 is the desired number of the manipulator boom positions in its range of movement; N_4 is the desired number of the stick positions in its range of movement for a certain position of the manipulator boom; N_5 is the desired number of the bucket positions in its range of movement for a certain position of the manipulator stick; N_w is 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} is the initial angle of the direction in which the digging resistance acts; θ_{wk} is the final angle of the direction in which the digging resistance acts; ρ_z is the density of the scooped material; V_z is the volume of the bucket; μ_p is the coefficient of adherence; a is the factor of the influence of the slewing bearing force; b is the factor of the influence of the radial bearing force; f_s is 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 (Figure 3), the program 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});

e) Equivalent slewing bearing loads (F_e, M_e).

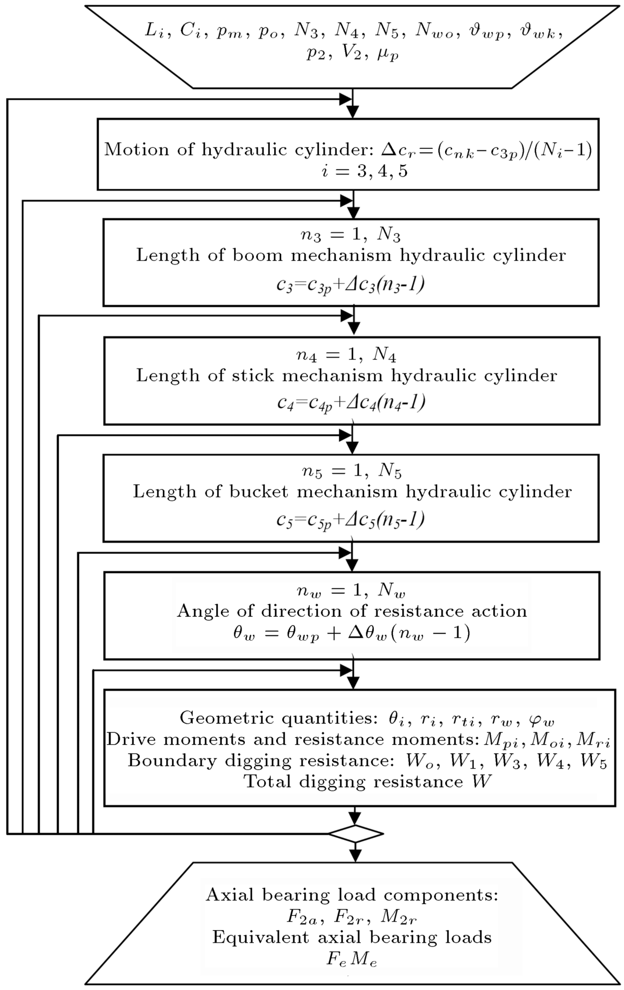

Figure 3. Algorithm of the program for the analysis of slewing bearing loads of a rotating platform drive in hydraulic excavators.

The program 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.

By comparing the spectrum of the equivalent bearing loads obtained through analysis with the permitted bearing loads provided in the bearing loading capacity diagrams, the reliable size of the bearing is selected.

4.1. Results and discussion

By using the developed program, the analysis of slewing bearing loads was performed for a rotating platform of a hydraulic excavator with the mass of 100000 kg and power of 400 kW with a backhoe attachment. The kinematic chain of the selected excavator size could be equipped with three different support and movement mechanisms with continuous tracks, three booms, L_3, (Figure 2), four sticks, L_4, of various lengths, and twelve buckets, L_5, of various volumes to

Table 1. Values of the input parameters of the program.

Parameters	p_m	p_o	N_3	N_4	N_5	N_w	θ_{wp}	θ_{wk}	μ_p	a	b	f_s
Values	32 MPa	1.2 MPa	30	20	10	10	30°	150°	0.85	1	2.05	1.45

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 (Figure 2), track distance of $B = 3600$ mm, and backhoe attachment with the boom of $s_3 = 7.2$ m in length, the stick of $s_4 = 2.9$ m in length, and the bucket with the volume of $V = 4,8$ m^3 for digging the material with the density of $\rho_z = 2200$ kg/m^3. Variant B of the excavator kinematic chain had a longer support and movement mechanism with the footprint length of $L = 5166$ mm, track distance of $B = 3600$ mm, and backhoe attachment with the boom of $s_3 = 10.5$ m in length, the stick of $s_4 = 5.8$ m in length, and the bucket with the volume of $V = 2$ m^3 for digging the material with the density of $\rho_z = 1800$ kg/m^3.

The input database of the program contained parameters (Table 1) which were the same for both variants A and B of the excavator kinematic chain.

On the basis of the set input parameters, using the developed program, 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 program 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 (Figure 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 bearing which differ in size (Figure 4,

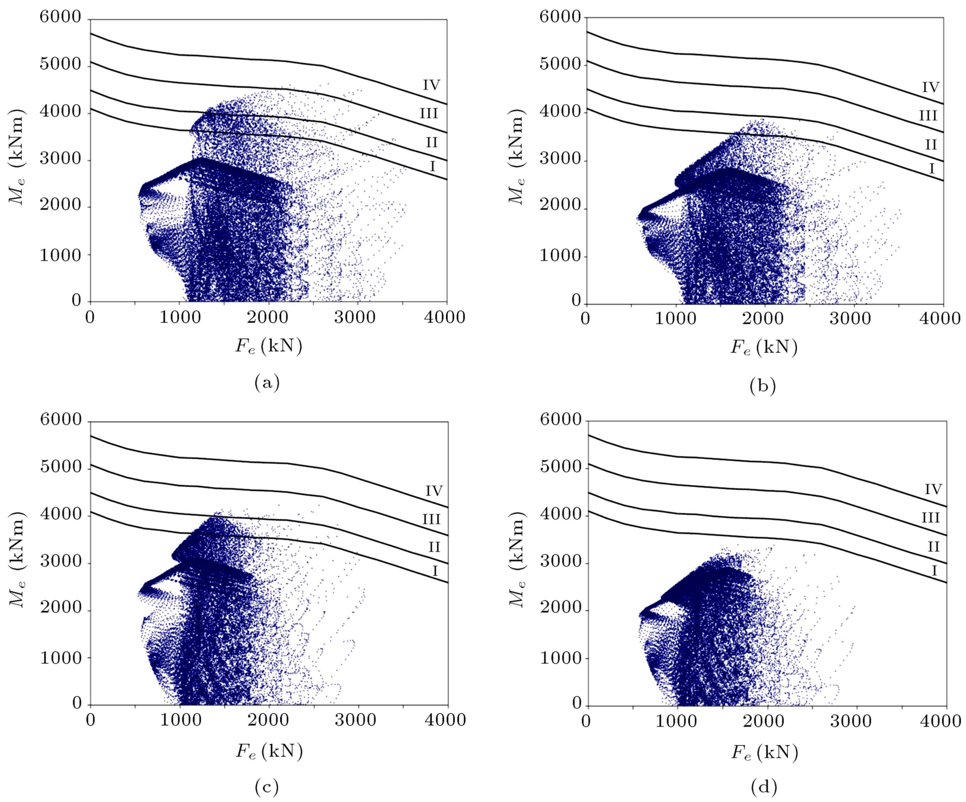

Figure 4. Spectra of slewing bearing load of a rotating platform drive of hydraulic excavators: (a) Variant A - longitudinal rollover line x-x; (b) variant A - transverse rollover line z-z; (c) variant B - longitudinal rollover line x-x; and (d) variant B - transverse rollover line z-z.

curves I, II, III, IV, V) [17]. 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) (Figure 4(a)) corresponds to the bearing size IV, while the transverse rollover line (z-z) (Figure 4(b)) 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) (Figure 4(c)) corresponds to the bearing size III, and the transverse rollover line (z-z) (Figure 4(d)) corresponds to the bearing size I.

Analysis results can also be presented in the form of the spectra of equivalent forces (Figure 5(a) and (c)) and equivalent moments (Figure 5(b) and (d)) of bearing loads depending on the digging coordinates (x_w, y_w) of the top of the cutting edge of the bucket 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 design information 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 a software was developed that enables a comprehensive analysis of equivalent slewing bearing loads of an excavator rotating platform which allows 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

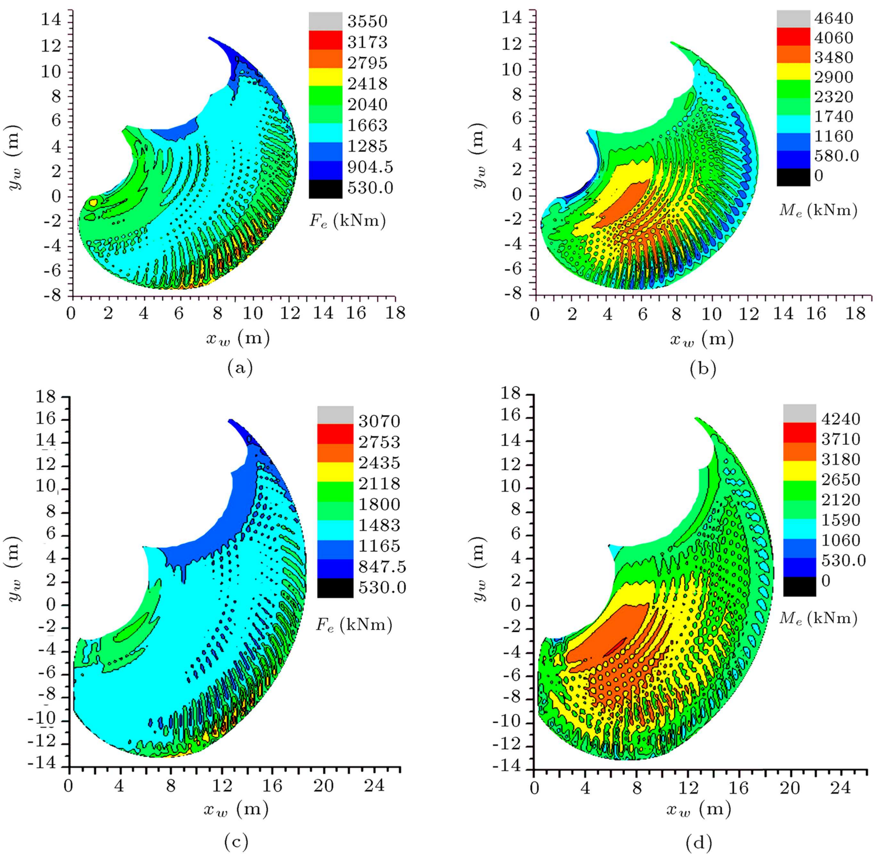

Figure 5. Spectra of equivalent bearing loads depending on the digging coordinates: (a) Spectrum of equivalent forces; (b) spectrum of equivalent moments for variant A and longitudinal rollover line x-x; (c) spectrum of equivalent forces; and (d) spectrum of equivalent moments for variant B and longitudinal rollover line x-x.

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.

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