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STUDY ON THE RELATIONSHIP BETWEEN STABILITY AND ENERGY EFFICIENCY OF HYDRAULIC EXCAVATORS

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ABSTRACT

The cycle of operation of hydraulic excavators has a series of steps in which large masses are accelerated and then braked. The presence of additional masses on the excavators improves stability but reduces energy efficiency. In this paper is examined the possibility of reducing energy consumption while maintaining an acceptable stability of the machine. The results of the analysis allow for some conclusions on how to achieve energy efficiency on the excavators.

KEYWORDS: mechanism, excavator, stability, energy efficiency

1. INTRODUCTION

In the functioning of the hydraulic excavators there are a number of limitations related to structural and functional aspects. One of the limitations is related to machine stability. Stability calculations are usually made without considering the inertial forces developed by the masses in motion. In this paper we will present an analysis of the influence of inertia forces on the stability of the excavators, seen in terms of energy efficiency of the machine.

The functioning of excavators is performed by a working cycle (Figure 1). Are represented active elements and how they enter and leave the action.

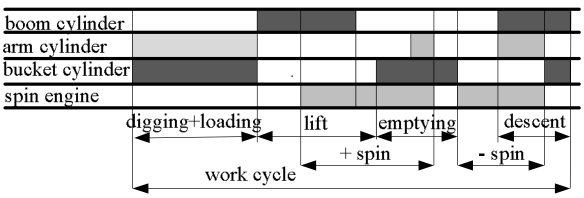

Fig. 1. The operating cycle of an excavator

In order to realize the operating cycle, the energy is consumed:

- Excavation;
- Lifting and handling equipment and load;
- Spins.

Energy consumption during the work cycle is not uniformly distributed in time. The work cycle must be conducted to ensure the stability of the machine. The excavator is under the action of a complex system of forces.

The kinetic energy accumulated because of inertial forces that affect machine stability.

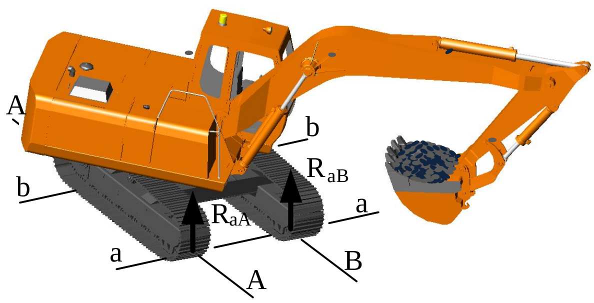

Fig. 2. Lines of overturning

Through stable equipment, we understand the situation in which he can not flip. The overthrow is possible after one of axes situated at ground level. Therefore, for stability, no single force from support points should become 0.

In reality, the pressure exerted by tracked excavator on uneven ground is variable. The pressure distribution depends on the track chain tension and the bottom rollers forces. A further influence is linked to the geometry of the ground. Also, the inclination of the axis of rotation of the excavator is important. In this paper, we consider assumptions in accordance with Figure 2.

2. ANALYSIS OF PLATFORM ROTATION

To analyze the rotation of moving parts of the excavator (Figure 3) are taken into consideration:

- The geometry of the assembly that rotates change over time;
- Rotation movement is done with variable angular velocity;
- Moments of inertia are changing depending on the charge status of the bucket.

Sizing calculations and checking for kinematics and energetic for excavators rely on a series of relationships [5]:

- Koenig's theorem of the angular momentum

$$\overline{K} = \sum_{i=1}^{n} \overline{r_i} \times m_i \cdot \overline{v_i} = \overline{\rho} \times M \cdot \overline{v_c} \qquad (1)$$

- Koenig's theorem on energy

$$E = \sum_{i=1}^{n} m_i \cdot v_i^2 = \frac{1}{2} M \cdot v_c^2 + E' \qquad (2)$$

-Steiner's theorem on the variation of the moments of inertia

$$J_\Delta = J_{\Delta 0} + M \cdot d^2 \qquad (3)$$

Fig. 3. Rotating Platform and working equipment

To achieve a cycle, are held two rotations:

-After digging, loading bucket and a partial lifting of equipment, begin the first rotation to get to the download position with loaded bucket;

- One rotation to return to the digging with an empty bucket.

In Figure 4 is shown the diagram of angular velocities and angular accelerations of the first phase. To reduce mechanical stresses and the risk of rollover it is desirable that the angular accelerations (starting and braking) be constant.

The energy required to realize the rotation (Figure 5) is given by the hydraulic system. It is powered by a heat engine, with limited power $N_{max\,t}$, which acts the hydraulic pump .

The hydraulic system sends hydraulic oil to the rotation mechanism of the rotating platform. The flow is generated by the pump group. The machine management system limits the power generated N_{max}.

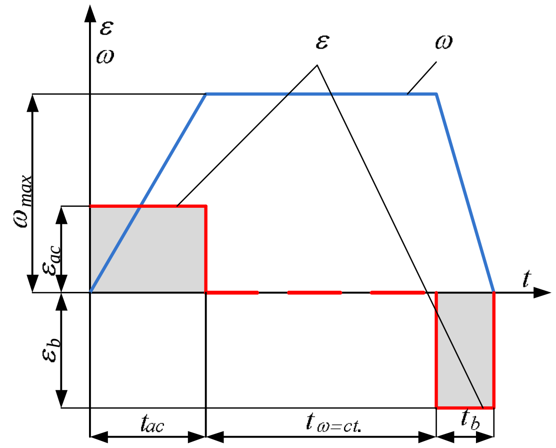

Fig. 4 Diagram angular velocities and accelerations

Are taken into account mechanical and hydraulic losses in the system by using efficiency factor η_{hm}

$$E = \frac{J_\Delta \cdot \omega_{max}^2}{2} = N_{max} \cdot \eta_{hm} \qquad (4)$$

Total angle of rotation of the platform and of the equipment

$$\theta_c = \frac{\varepsilon_{ac} \cdot t_{ac}^2}{2} + \omega_{max} \cdot \left(t_{\theta_c} - t_{ac} - t_b\right) + \frac{\varepsilon_b \cdot t_b^2}{2} \qquad (5)$$

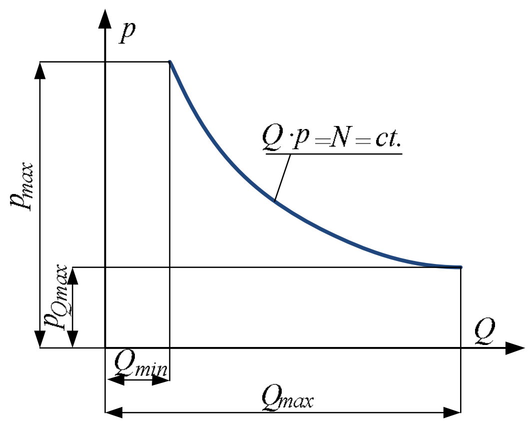

Fig.5. The acceleration of some important points

2. THE DYNAMIC OF ROTATION FOR THE PLATFORM AND DIGGING EQUIPMENT

The study of the excavator stability can be achieved in different hypotheses, depending on the desired accuracy of the calculation:

- All in motion elements, including the load of bucket, are equated in a single center of mass;

- All in motion elements, including the load of bucket are equated in a number of centers of mass, conveniently chosen.

Another aspect is the consideration of partial overlapping of the rotational and lifting motion of the equipment.

Depending on the assumptions chosen, it is determined the mass characteristics of elements and their positions in the system.

In Figure 5 three points were considered centers of mass:

- C_{GP} for the rotating platform;
- C_{GE} for the excavation equipment;
- C_{GL} for the bucket load.

When rotating in the other sense it is considered another position of digging equipment and the load is remove.

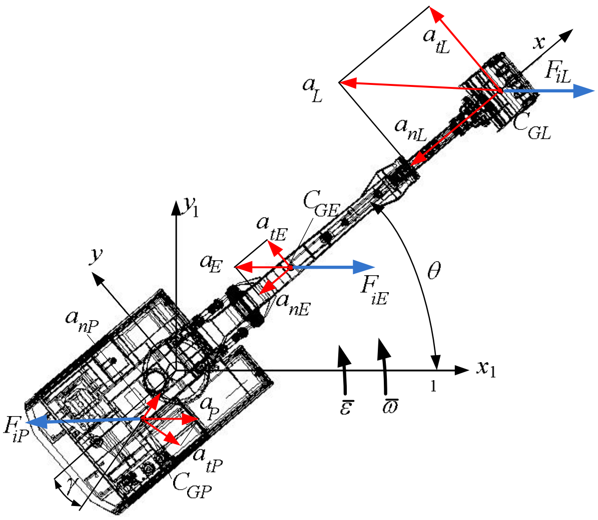

Fig. 6. The accelerations of mass centers of components

Starting from the 3D designs of elements, the mass properties of components can be determined. The determinations it can be made and for groups of elements considered depending on the position of the equipment.

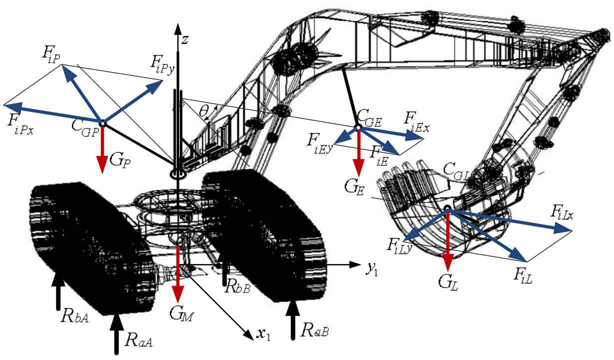

Fig.7. Forces that occur in the centers of mass of the excavator during rotation

Knowing these characteristics can be determined accelerations in points of interest.

In Figure 6 are represented the accelerations of the centers of mass. Starting from the accelerations and mass characteristics can be determined the forces acting on the centers of mass.

In Figure 7 are represented forces of inertia and weight of the items considered as acting in those centers of mass.

The forces considered have the expressions:

$$\begin{aligned} F_{iLx} &= \omega^2 \cdot x_{C_{GL}} \cdot m_{C_{GL}} \\ F_{iLy} &= \varepsilon \cdot x_{C_{GL}} \cdot m_{C_{GL}} \end{aligned} \tag{6}$$

$$\begin{aligned} F_{iEx} &= \omega^2 \cdot x_{C_{GE}} \cdot m_{C_{GE}} \\ F_{iEy} &= \varepsilon \cdot x_{C_{GE}} \cdot m_{C_{GE}} \end{aligned} \tag{7}$$

and for the rotating platform, with

$$\begin{aligned} \gamma &= atn\left(\frac{y_{GP}}{x_{GP}}\right) \\ R_{GP} &= \sqrt{x_{GP}^2 + y_{GP}^2} \end{aligned} \tag{8}$$

resulting

$$\begin{aligned} F_{iPn} &= \omega^2 \cdot x_{C_{GP}} \cdot m_{C_{GP}} \\ F_{iPt} &= \varepsilon \cdot x_{C_{GP}} \cdot m_{C_{GP}} \end{aligned} \tag{9}$$

To develop calculations, the forces are reduced on $O_1z_1 \equiv Oz$ axis , resulting:

- Forces due to concentrated mass $m_{C_{GL}}$ from point $0,0,z_{1C_{GL}}$

$$\begin{cases} F_{iLx} \Rightarrow F_{iLx} \\ F_{iLy} \Rightarrow F_{iLy}, M_{iLz} = x_{C_{GL}} \cdot F_{iLy} \\ G_L \quad \Rightarrow G_{Lz} = G_L, M_{iLy} = x_{C_{GL}} \cdot G_L \end{cases} \tag{10}$$

- Forces due to concentrated mass $m_{C_{GE}}$ from point $0,0,z_{1C_{GE}}$

$$\begin{cases} F_{iEx} \Rightarrow F_{iEx} \\ F_{iEy} \Rightarrow F_{iEy}, M_{iEz} = x_{C_{GE}} \cdot F_{iEy} \\ G_E \quad \Rightarrow G_{Ez} = G_E, M_{iEy} = x_{C_{GE}} \cdot G_E \end{cases} \tag{11}$$

- Forces due to concentrated mass $m_{C_{GP}}$ from point $0,0,z_{1C_{GP}}$

$$\begin{cases} F_{iPn} \Rightarrow F_{iPnx} = F_{iPn} \cdot \cos\gamma, F_{iPny} = F_{iPn} \cdot \sin\gamma \\ F_{iPt} \Rightarrow F_{iPtx} = F_{iPt} \cdot \sin\gamma, F_{iPty} = F_{iPt} \cdot \cos\gamma, \\ M_{iPz} = R \cdot F_{iPt} \\ G_P \quad \Rightarrow G_{Pz} = G_P, M_{Px} = R \cdot \sin\gamma \cdot G_P, \\ M_{Px} = R \cdot \cos\gamma \cdot G_P \end{cases} \tag{12}$$

For the stability study, between the reduced parameters to the axis Oz, are interest all forces and moments on directions o1x and oy .

To simplify the calculations, the forces and moments directed on Ox o1x and Oy oy are projected on the $O_1x_1y_1z_1$ system.

The rules to pass from one system to another are

$$\begin{aligned} &F_{xk}\ produce \begin{cases} F'_{xk1} = F_{xk} \cdot \cos\theta \\ F'_{yk1} = F_{xk} \cdot \sin\theta \end{cases} \\ &F_{yk}\ produce \begin{cases} F''_{xk1} = F_{yk} \cdot \sin\theta \\ F''_{yk1} = F_{yk} \cdot \cos\theta \end{cases} \end{aligned} \tag{13}$$

and

$$\begin{aligned} &M_{xk}\ produce \begin{cases} M'_{xk1} = M_{xk} \cdot \cos\theta \\ M'_{yk1} = M_{xk} \cdot \sin\theta \end{cases} \\ &M_{yk}\ produce \begin{cases} M''_{xk1} = M_{yk} \cdot \sin\theta \\ M''_{yk1} = M_{yk} \cdot \cos\theta \end{cases} \end{aligned} \tag{14}$$

Follows the reduction in O_1 of mechanical moments and forces.

$$\begin{cases} M_{xk} = \sum M_{xk} + \sum F_{yk} \cdot z \\ F_{zO1} = \sum F_{zk} \end{cases} \tag{15}$$

The equation from which is determined the stability takes into account the mechanical equilibrium the face of the line against which it assesses the possibility of overturning. For instance, if it is considered overturning in relation to line BB (Figure 2), we get

$$M_{x1} + \left(F_{z01} + G_M\right) \cdot \frac{d_s}{2} = \frac{R_{AA}}{2} \tag{16}$$

where d_s is the distance between tracks and R_{AA} is the sum of the vertical reactions on the line AA. If $R_{AA} \geq 0$, the machine is stable.

4. CONCLUSIONS

Using 3D design facilities of accurate data can be obtained the characteristics of the mass of machinery and components. Through optimizing placements for masses in rotation we can get a compromise between reducing the energy required for rotation and the machine stability.

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