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Optimization of the Parameters of a Hydraulic Excavator Swinging Mechanism

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Abstract*— *The presented paper is focused to the optimization of the parameters of a hydraulic excavator swinging mechanism. A trapezoidal velocity profile is considered for rotation of the excavator platform to the predefined angle. Equations for the torque and power, needed to rotate the platform according to the prescribed trapezoidal trajectory are derived. The maximum values of the driving torque and power are optimized.

***Keywords*— hydraulic excavator, swinging mechanism, optimization.**

I. INTRODUCTION

The hydraulic excavator is a multifunctional earth moving machine, widely used in the construction and mining industry. Its swinging mechanism is intended to rotate the excavator platform together with the front digging manipulator about a vertical axis. It does not participate directly in the earthmoving operations and has auxiliary functions, mainly by performing the transport operations of the excavated soil, as well as the positioning of the digging manipulator in the required position [1]. Typically [2], the motion of the prime mover is transferred to the platform by a powertrain, which consists of a hydraulic pump, of an axial-piston hydraulic motor (Fig.1, pos.1) coupled to a vertical two-stage planetary gearbox (Fig.1, pos.2), whose output shaft with the coupled small sprocket is engaged with the slewing bearing toothed ring (Fig.1,pos.3).

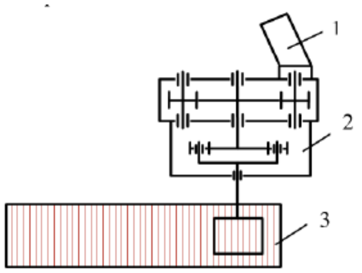

Fig.1: Kinematic scheme of the excavator swinging mechanism

The motion trajectory of the rotational platform $\varphi_{pl}(t)$ (Fig.2) determines the kinematic and dynamic properties of the swinging mechanism components, including the prime mover, as well as the ergonomic characteristics of the operator.

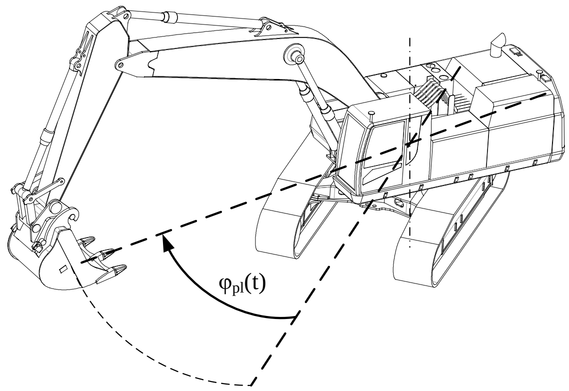

Fig.2: Angle of rotation of the platform

Different trajectories $\varphi_{pl}(t)$ are possible to use [3] including widely used linear segment joined with parabolic blends. For the linear segment the velocity is constant, while for the parabolic blends the velocity is a linear function of the time, that is why the velocity profile is called trapezoidal velocity profile. The rotation of the platform is divided into three phases: 1) acceleration phase, characterized by a linear increase of the velocity, a positive acceleration and a parabolic increase of the rotation angle; 2) phase of the constant velocity, characterized by a zero acceleration and linear increase of the rotation angle; 3) deceleration phase, characterized by a linear decrease of the velocity, a negative acceleration and a parabolic increase of the rotation angle. In the most cases, the acceleration and the deceleration phases have the same duration. Although the acceleration is discontinuous and contributes to the producing of vibrational effects in the mechanical systems with structural elasticity, this type of motion law is widely used [4] due to its simplicity and wide use in the real applications.

II. KINEMATIC MODEL

Fig. 3 depicts the trapezoidal velocity profile, where by $\dot{\varphi}_{pl}^{\max}$ is denoted the constant angular velocity of the platform, by Δt is denoted the duration of the acceleration/deceleration phase, and by t_f is denoted the total duration of the rotation.

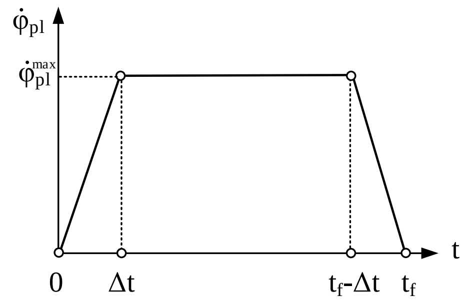

Fig.3: Trapezoidal velocity profile

If by φ_{pl}^{f} is denoted the value of the needed angle of rotation and by $\ddot{\varphi}_{pl}^{tr}$ - the angular acceleration during the acceleration and deceleration phases then the considered motion law is represented by the following piecewise defined function:

$$\varphi_{pl} = \begin{cases} \dfrac{\ddot{\varphi}_{pl}^{tr}}{2} t^2, & 0 \le t \le \Delta t \\ \dfrac{1}{2}\left(\varphi_{pl}^{f} + \dot{\varphi}_{pl}^{\max}\left(2t - t_f\right)\right), & \Delta t < t \le t_f - \Delta t \\ \varphi_{pl}^{f} - \dfrac{\ddot{\varphi}_{pl}^{tr}}{2}\left(t - t_f\right)^2, & t_f - \Delta t < t \le t_f \end{cases} \quad (1)$$

and therefore, the angular velocity and acceleration are:

$$\dot{\varphi}_{pl} = \omega_{pl} = \begin{cases} \ddot{\varphi}_{pl}^{tr} t, & 0 \le t \le \Delta t \\ \dot{\varphi}_{pl}^{\max}, & \Delta t < t \le t_f - \Delta t \\ \ddot{\varphi}_{pl}^{tr}\left(t_f - t\right), & t_f - \Delta t < t \le t_f \end{cases} \quad (2)$$

$$\ddot{\varphi}_{pl} = \varepsilon_{pl} = \begin{cases} \ddot{\varphi}_{pl}^{tr}, & 0 \le t \le \Delta t \\ 0, & \Delta t < t \le t_f - \Delta t \\ -\ddot{\varphi}_{pl}^{tr}, & t_f - \Delta t < t \le t_f \end{cases} \quad (3)$$

where

$$\Delta t = \frac{\dot{\varphi}_{pl}^{\max}}{\left|\ddot{\varphi}_{pl}^{tr}\right|} \quad (4)$$

The duration of the platform rotation is presented by the following equation:

$$t_f = \frac{\varphi_{pl}^{f}}{\dot{\varphi}_{pl}^{\max}} + \frac{\dot{\varphi}_{pl}^{\max}}{\left|\ddot{\varphi}_{pl}^{tr}\right|} \quad (5)$$

Equation (5) can be represented as a quadratic equation in relation to $\dot{\varphi}_{pl}^{\max}$:

$$\left(\dot{\varphi}_{pl}^{\max}\right)^2 - t_f\left|\ddot{\varphi}_{pl}^{tr}\right|\dot{\varphi}_{pl}^{\max} + \varphi_{pl}^{f}\left|\ddot{\varphi}_{pl}^{tr}\right| = 0 \quad (6)$$

and then by using (4), eq. (6) takes the following form:

$$\ddot{\varphi}_{pl}^{tr}\Delta t^2 - t_f\ddot{\varphi}_{pl}^{tr}\Delta t + \varphi_{pl}^{f} = 0 \quad (7)$$

The equation (7) can be represented as:

$$\ddot{\varphi}_{pl}^{tr} = \frac{\varphi_{pl}^{f}}{\Delta t\left(t_f - \Delta t\right)} \quad (8)$$

Also, the following equation is valid:

$$\Delta t = \frac{\dot{\varphi}_{pl}^{\max} t_f - \varphi_{pl}^{f}}{\dot{\varphi}_{pl}^{\max}} \quad (9)$$

III. TORQUE AND POWER MODEL

The reduced to the platform axis of rotation driving torque M_{pl} is represented as a sum of the following torques [5, 6]:

$$M_{pl} = M_{pl}^{st} + M_{pl}^{dyn} \quad (10)$$

where M_{pl}^{st} is a static torque, exerted mainly by the slewing bearing resistive forces and wind forces; M_{pl}^{dyn} - dynamic torque, exerted by the inertial forces of the platform and powertrain elements.

The dynamic torque is calculated as:

$$M_{pl}^{dyn} = J\ddot{\varphi}_{pl} \quad (11)$$

where J is the total mass moment of inertia of the rotational platform together with the front digging manipulator and the powertrain elements, reduced to the axis of rotation of the platform.

Using (3), the torque equation (10) obtains the following form:

$$M_{pl} = M_{pl}^{st} + J\begin{cases} \ddot{\varphi}_{pl}^{tr}, & 0 \le t \le \Delta t \\ 0, & \Delta t < t \le t_f - \Delta t \\ -\ddot{\varphi}_{pl}^{tr}, & t_f - \Delta t < t \le t_f \end{cases} \quad (12)$$

and its maximum value is during the acceleration phase:

$$M_{pl}^{\max} = M_{pl}^{st} + J\ddot{\varphi}_{pl}^{tr} \quad (13)$$

By the use of (8), $M_{pl}^{\max}$ is represented as a function of Δt and t_f:

$$M_{pl}^{\max} = M_{pl}^{st} + J\frac{\varphi_{pl}^{f}}{\Delta t\left(t_f - \Delta t\right)} \quad (14)$$

The power, needed to drive the platform P_{pl} is:

$$P_{pl} = M_{pl}\dot{\varphi}_{pl} \quad (15)$$

Taking into account (10), the power is computed as:

$$P_{pl} = \left(M_{pl}^{st} + J\ddot{\varphi}_{pl}\right)\dot{\varphi}_{pl} \quad (16)$$

By the use of (2) and (3), (16) is represented as:

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$$P_{pl}=\begin{cases} M_{pl}^{st}\ddot{\varphi}_{pl}^{tr}t+J\left(\ddot{\varphi}_{pl}^{tr}\right)^2 t, \\ if\ 0\le t\le \Delta t \\ M_{pl}^{st}\dot{\varphi}_{pl}^{\max}, \\ if\ \Delta t<t\le t_f-\Delta t \\ M_{pl}^{st}\ddot{\varphi}_{pl}^{tr}\left(t_f-t\right)-J\left(\ddot{\varphi}_{pl}^{tr}\right)^2\left(t_f-t\right), \\ if\ t_f-\Delta t<t\le t_f \end{cases} \quad (17)$$

As can be seen, the maximum of the needed power is at the end of the acceleration phase and its value is:

$$P_{pl}^{\max}=M_{pl}^{st}\ddot{\varphi}_{pl}^{tr}\Delta t+J\left(\ddot{\varphi}_{pl}^{tr}\right)^2\Delta t \quad (18)$$

By using (4), the equation for the maximum value of the power is represented as:

$$P_{pl}^{\max}=M_{pl}^{st}\dot{\varphi}_{pl}^{\max}+J\frac{\left(\dot{\varphi}_{pl}^{\max}\right)^2}{\Delta t} \quad (19)$$

From (9) it follows that:

$$\dot{\varphi}_{pl}^{\max}=\frac{\varphi_{pl}^{f}}{t_f-\Delta t} \quad (20)$$

By inserting (20) in (19), for the maximum value of the power one obtains:

$$P_{pl}^{\max}=\frac{\varphi_{pl}^{f}\left(M_{pl}^{st}t_f\Delta t-M_{pl}^{st}\left(\Delta t\right)^2+\varphi_{pl}^{f}J\right)}{\Delta t\left(t_f-\Delta t\right)^2} \quad (21)$$

As one can see, for known values of φ_{pl}^{f}, M_{pl}^{st} and J, the equations for the maximum torque (14) and the maximum power (21) are functions of the duration of the rotation t_f and the duration Δt of the acceleration/ deceleration periods, so their optimal values could found.

IV. OPTIMIZATION OF THE MAXIMUM DRIVING TORQUE VALUE

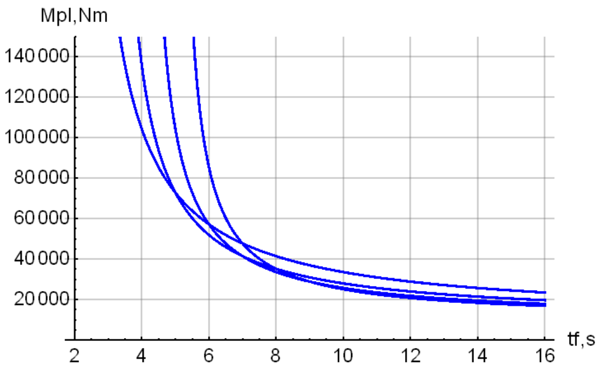

Fig.4: Driving torque as a function of the duration of the rotation

Fig.4 depicts the driving torque, computed according to (14) as a function of the duration of the rotation t_f for the values of $\Delta t=2{,}3{,}4$ and 5 s. and: $M_{pl}^{st}=10kNm$, $\varphi_{pl}^{f}=\pi$, $J=120.10^3\,kgm^2$. In Fig.5 is shown the driving torque as a function of the acceleration phase duration for t_f=12s and $M_{pl}^{st}=10kNm$, $\varphi_{pl}^{f}=\pi$, $J=120.10^3\,kgm^2$.

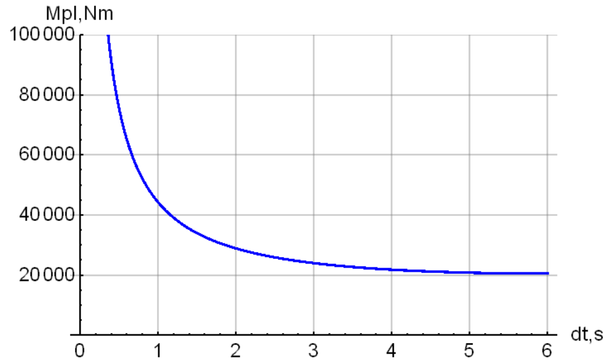

Fig.5: Driving torque as a function of the acceleration phase duration

As one can see from Fig.4 and Fig.5, the increase of the duration of the rotation t_f and the duration Δt of the acceleration/deceleration periods unambiguously decreases the value $M_{pl}^{\max}$ of the maximum torque.

If the value of the maximum driving torque is limited to the value $\left[M_{pl}^{\max}\right]$ and (14) is solved for t_f, then the following function $t_f\left(\Delta t\right)$ is obtained:

$$t_f=\Delta t+\frac{J\varphi_{pl}^{f}}{\left(\left[M_{pl}^{\max}\right]-M_{pl}^{st}\right)\Delta t} \quad (22)$$

The structure of this equation suggests that optimization by numerical or analytical methods [7] of the duration t_f is possible. In Fig.6 is shown the graph of the function $t_f\left(\Delta t\right)$ for $\left[M_{pl}^{\max}\right]=30$, 60, 90, 120 and 150 kNm.

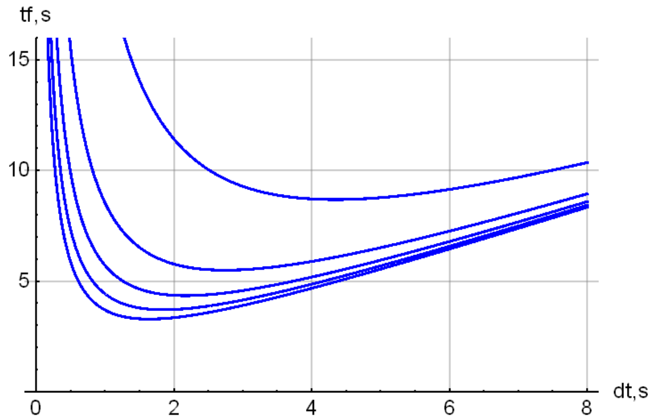

Fig.6: The function $t_f\left(\Delta t\right)$

The objective function is:

$$t_f\left(\Delta t\right)\rightarrow\min \quad (23)$$

and the following constraint must be satisfied:

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$$0 < \Delta t \leq \frac{t_f}{2} \tag{24}$$

The minimum of the function (22) is determined analytically by the solution of the following equation:

$$\frac{dt_f}{d(\Delta t)} = 0 \tag{25}$$

which leads to:

$$1 - \frac{J\varphi_{pl}^f}{\left(\left[M_{pl}^{\max}\right] - M_{pl}^{st}\right)\Delta t^2} = 0 \tag{26}$$

From (26) it can be found that the optimal value of Δt is:

$$\Delta t^* = \sqrt{\frac{J\varphi_{pl}^f}{\left(\left[M_{pl}^{\max}\right] - M_{pl}^{st}\right)}} \tag{27}$$

V. OPTIMIZATION OF THE MAXIMUM POWER VALUE

Fig.7 depicts the driving power, computed according to (21) as a function of the duration of the rotation t_f for the value of $\Delta t = 2$ s., $M_{pl}^{st} = 10kNm$, $\varphi_{pl}^f = \pi$, $J = 120.10^3 kgm^2$. As one can conclude, the increase of the duration of the rotation t_f unambiguously decreases the value $P_{pl}^{\max}$.

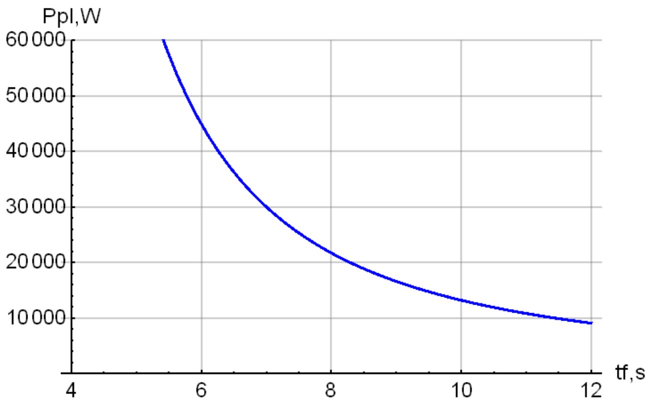

Fig.7: The driving power, as a function of the duration of the rotation

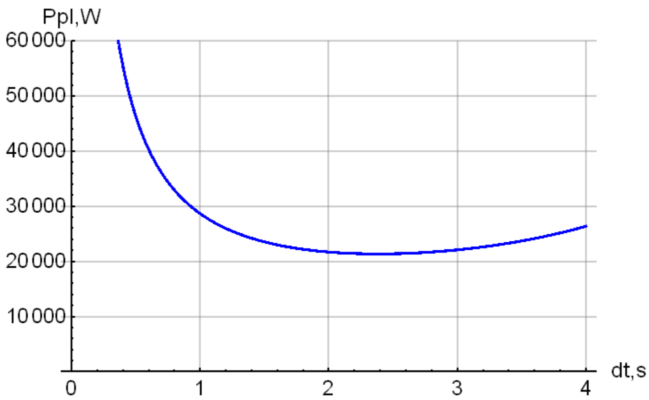

Fig.8: The driving power as a function of Δt

Fig.8 depicts the change of the driving power as a function of Δt for the value of t_f=8 s., $M_{pl}^{st} = 10kNm$, $\varphi_{pl}^f = \pi$, $J = 120.10^3 kgm^2$. As one can see there is a well-marked minimum of the power for a certain value of Δt.

It is possible to determine Δt for which $P_{pl}^{\max}$ is minimized. The objective function is:

$$P_{pl}^{\max}(\Delta t) \to \min \tag{28}$$

Subjected to the constraint (24).

By computing

$$\frac{dP_{pl}^{\max}}{d(\Delta t)} = 0 \tag{29}$$

one obtains the following cubic equation:

$$M_{pl}^{st}\Delta t^3 - M_{plc}^{st} t_f \Delta t^2 - 3\varphi_{pl}^f J\Delta t + \varphi_{pl}^f J t_f = 0 \tag{30}$$

Two approaches are possible to solve eq. (30) in relation to Δt:

- If the static power is much smaller then the dynamic one, then in (30) M_{pl}^{st} is neglected and only the dynamic power is minimized. In this case the solution leads to the following value for the optimal duration of the acceleration phase:

$$\Delta t^* = \frac{t_f}{3} \tag{31}$$

- If the static power cannot be neglected, then the cubic eq. (30) is solved by analytical or numerical methods [8]. The value of Δt^* is chosen satisfying constraint (24).

VI. CONCLUSIONS

This paper presents an approach for optimization of the parameters of a hydraulic excavator swinging mechanism. A trapezoidal velocity profile is considered for rotation of the excavator platform to the predefined angle. Equations for the driving torque and power, needed to rotate the platform according to the prescribed trapezoidal trajectory are derived. The maximum values of the needed driving torque and power are optimized.

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