MODELLING AND SIMULATION OF THE STERILE ROCKS EXCAVATION PROCESS USING BUCKET WHEEL EXCAVATORS

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Abstract: This paper presents the modeling and simulation of the sterile rocks excavation process using bucket rotor excavators. The modeling and simulation of the excavation process is carried out in Matlab-Simulink, based on an original mathematical model of the momentary capacity.

Keywords: bucket wheel excavator, induction motors; scalar control system

1. INTRODUCTION

The excavation process of sterile rocks can be done in a cost-effective manner, both technically and energetically, only when the parameters characterizing this process, their interdependence, and the ways to improve the technical-economic indices that define the phenomenon of excavation are known.

Defining the excavation parameters, establishing them, as well as finding the relationships of interdependence, represents an important and not at all negligible problem if it is desired to know the excavation process in its depth.

Knowing these aspects does not solve the problem without performing a technological analysis of the excavation process. For this reason, this paper presents the analysis by modeling and simulation in the Matlab Simulink of the excavation process of the sterile rocks by means of bucket rotor excavators.

The analysis of the technological process of excavation is a research area dealt

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with over the past decade by several researchers including: Bosnjak (2006), Dandea (2013), Durst (1988), Haliti (2016), Jevtovic (2004), Ladanyi (2006), Nan (2007), Nan (2008), Pajer (1971), Petrovic (2006), Rasper (1975), Sharma (2009), Vetrov (1971).

The most important aspect of the current research, regarding the automatic driving of the bucket rotor excavators is the relatively constant maintenance with minimal variations of the material flow on the conveyor, within a swinging cycle of the excavator. Among the most recent research in this regard, we mention the following: Bosnjak (2015), Che (2014), Dandea (2013).

The main two advantages of constantly maintaining the flow of material on the conveyor belt are: reducing energy consumption and increasing the reliability of the components of the transport technology system. By constantly maintaining the flow of material on the conveyor belt, all machinery that is part of the transport technology flow can be chosen optimally so that they can be used intensively at nominal capacity. In the simulation of the excavation process in this article, are surprised the dynamic effects introduced by the induction machines and the gearboxes acting on the port-cups wheel and the excavator's top platform. In the simulation of the port - cup wheel drive system, the gear shifter of this system is also considered. Following the simulations are present and analyzed the variations in time of the flow coal load on the conveyor belt, variations in time of the pivoting speed and of the cutting speed over time for two distinct pivoting cycles. Simulations are customized for the EsRc 1400 rotor excavator. The results obtained from the research conducted in this article allow to highlight the possibilities of improving the cutting-loader system of the bucket rotor.

2. THE MOMENTARY CAPACITY

The most commonly used technology for mechanized extraction of lignite at the sur-face, is based on the excavation of the working steps above the level of the excavator, and based on the method of excavation with vertical multi-row chips (see Fig. 1).

In Fig. 1, the following notations were used: H_t is height of the working step; H_i the height of the slice i, (i=1 ÷ 4); D represent the rotor cutting diameter; a the axis of rotation of the bucket wheel arrow; b the axis of rotation of the upper plat-form; L_{sp} is distance between the axis of rotation of the bucket wheel arrow and the axis of rotation of the upper platform; H_s is height of axis of boom rotation to the level of operating the excavator; γ_i (i=1 ÷ 4) represents the apex angle of the bucket wheel boom to plane $X_b0_bZ_b$; L_s is bucket wheel boom length; θ is the bucket wheel boom position angle to axis 0_bX_b; h_0 is the maximum cutting depth; h_p is the width of the cut defined by the distance between the moving adjacent scoops and pass though the horizontal plane $X_b0_bZ_b$; α_1 is the angle in horizontal plane between the axis system $X_c0_rZ_c$ and the axis system $X_p0_rZ_p$; α_2 is the angle in vertical plane between the axis system $Y_p0_rZ_p$ and the axis system $Y_r0_rZ_r$; L_e is the distance between d (resulted after projecting c onto the horizontal plane $X_c0_rZ_c$) and 0_r in the horizontal plane $X_c0_rZ_c$, this distance defines the eccentricity of the bucket wheel in the horizontal plane; L_f is the distance between c and d in the vertical plane $Y_c0_rZ_c$, this distance defines the eccentricity of the bucket wheel in the vertical plane; ε is the inclination angle in horizontal plane measured between axis 0_rZ_p and the line which passes through 0_r and d; r is the distance between the rotation plane $0_rX_rY_r$ and the cutting plane $0_rX_tY_t$.

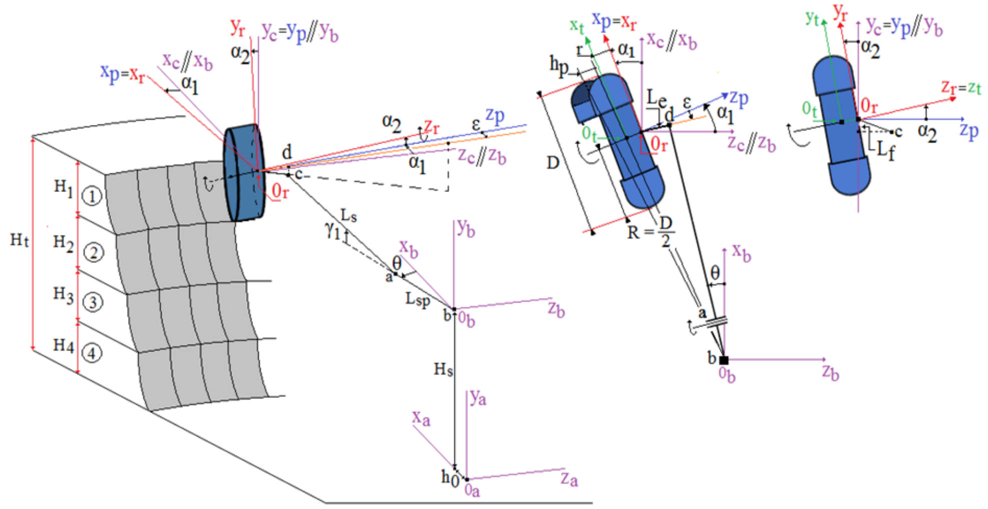

Fig. 1. Excavation with vertical multi-row chips

From the Fig. 1 it is observed that the cutting process is done by combining the rotation of the bucket wheel in the vertical cutting plane and the slewing of the upper platform of the excavator in the horizontal plane $X_b0_bZ_b$.

The main parameters of the cutting process described in Fig. 1, for $\alpha_1 = \alpha_2 = \varepsilon = 0^{\circ}$ and $L_e = L_f = r = 0$, are represented in Fig. 2.

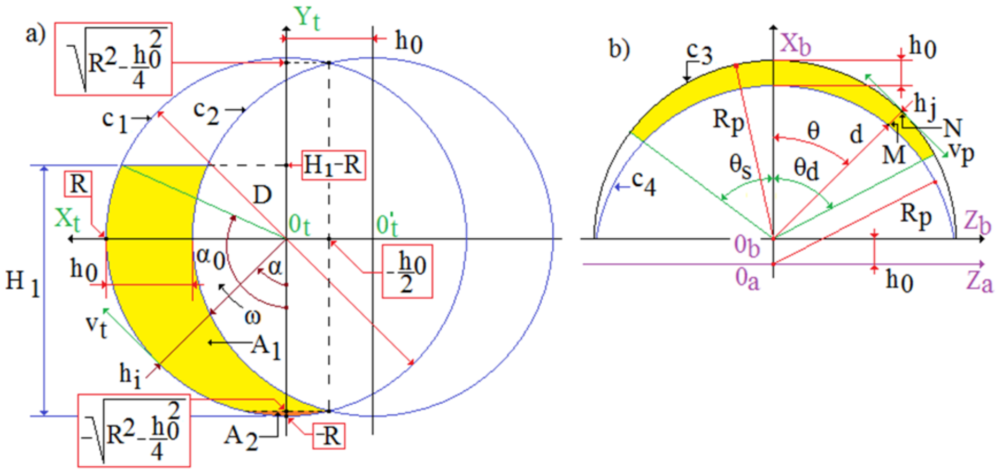

Fig. 2. The parameters of the cutting process.
a) in the main vertical plane; **b)** in the main horizontal plane.

The momentary capacity of excavating of the bucket wheel excavators can be obtained with the following expression

$$Q_m(\theta) = \frac{n_c \cdot n_t}{60} \cdot \int_{\theta}^{\theta + \frac{2\cdot\pi}{n_c} \cdot \frac{n_p}{n_t}} A_j(\theta_m) \cdot \left[R_p - R + x_c^j(\theta_m) \right] d\theta_m \tag{1}$$

where:

- A_j is the surface of the cut in a cutting plane situated at an angle θ in relation to the main plane

$$A_j = h_j \cdot (H_1 - R) + \frac{\pi \cdot R^2}{2} - R^2 \cdot \text{asin}\left(\sqrt{1 - \frac{h_j^2}{4 \cdot R^2}} \right) + \frac{h_j}{2} \cdot R \cdot \sqrt{1 - \frac{h_j^2}{4 \cdot R^2}} \tag{2}$$

- x_c^j is the abscissa of the centroid chip in the main vertical plane

$$x_c^j = \frac{1}{A_j} \cdot \left[\frac{h_j \cdot (R - H_1) \cdot (h_j - M_a)}{2} + \frac{2 \cdot R^3}{3} - \frac{(2 \cdot R^2 + h_j^2) \cdot \sqrt{4 \cdot R^2 - h_j^2}}{6} + \frac{R^2 \cdot h_j \cdot \delta_j}{2} \right] \tag{3}$$

$$\delta_j = a\sin\left(\sqrt{1 - \frac{h_j^2}{4 \cdot R^2}} \right) + a\sin\left(\frac{H_1}{R} - 1 \right); M_a = \sqrt{2 \cdot H_1 \cdot R - H_1^2} \tag{4}$$

- h_j is the distance between M and N points

$$h_j = \left| R_p + h_0 \cdot \cos(\theta) - \sqrt{R_p^2 - h_0^2 \cdot \sin^2(\theta)} \right| \tag{5}$$

In the above relationships, or use the following notations: n_c is number of spoons, n_t is speed of the wheel with spoons, R_p represents the slewing radius, $| \cdot |$ is absolute value and n_p is slewing speed.

Under these conditions, it was kept in mind that the time of the cycle for discharging a spoon, ΔT is equal to the running time h_p of the distance between the moving adjacent spoons and pass through the main horizontal plane, the capacity of excavation for any moment in time is defined by the following:

$$Q_m(t) = \frac{n_c \cdot n_t}{60} \cdot \int_{\theta_1}^{\theta_2} A_j\left(\theta_m - \frac{\pi}{2} \right) \cdot \left[R_p - R + x_c^j\left(\theta_m - \frac{\pi}{2} \right) \right] d\theta_m \tag{6}$$

where:

$$\theta_1 = \frac{2 \cdot \pi \cdot n_p}{60} \cdot floor\left[\frac{t}{\Delta T}\right] + \theta_0 \cdot \frac{\pi}{180} \tag{7}$$

$$\theta_2 = \theta_1 + \frac{2 \cdot \pi}{n_c} \cdot \frac{n_p}{n_t} \tag{8}$$

$$\Delta T = \frac{1}{z} = \frac{60}{n_c \cdot n_t} \tag{9}$$

In the expression (7), Θ_0 represents the initial slewing angle and *floor[x]* is the largest integer equal to or less than *x*.

If the final angle of slewing Θ_f is known, the period for excavating a cutting on a certain slice can be calculated with the following expression:

$$t_f = \frac{10}{n_p \cdot n_c^2 \cdot n_t^2} \cdot \left[n_c \cdot n_t \cdot \left(\theta_f - \theta_0\right) - 360 \cdot n_p \right] \tag{10}$$

Additionally, using the Gaussian quadrature formula in 3 points, formula (6) becomes:

$$Q_m\left(t\right) = \frac{n_c \cdot n_t}{60} \cdot \frac{\theta_2 - \theta_1}{2} \cdot \sum_{i=0}^{3} M_i \cdot f_1\left(\frac{\theta_2 - \theta_1}{2} \cdot g_i + \frac{\theta_2 + \theta_1}{2}\right) \tag{11}$$

where:

$$f_1\left(x\right) = A_j\left(x - \frac{\pi}{2}\right) \cdot \left[R_p - R + x_c^j\left(x - \frac{\pi}{2}\right)\right] \tag{12}$$

$$M_1 = M_3 = \frac{5}{9}; M_2 = \frac{8}{9} \tag{13}$$

$$-g_1 = g_3 = \sqrt{\frac{3}{5}}; g_2 = 0 \tag{14}$$

From the expression (11) it is visible that when the speed of the bucket wheel with spoons (n_t) is kept at a constant value, then the momentary excavating capacity is directly proportional with the slewing speed (n_p).

In the simulation of the excavation process, we will consider that the flow of material loaded onto the conveyor belt from the rotor excavator component is given by the following relation:

$$Q\left(t\right) = Q_m\left(t\right) - Q_n\left(t\right) \tag{15}$$

where:

$$Q_n(t) = k_0 \cdot |\theta_1| \tag{16}$$

is the lost flow in the load process, which is directly proportional to the pivot angle Θ_1.

The factor k_0 from formula (16), is a random number from interval [0% ... 5%]$\cdot Q_m$.

3. SIMULATION OF THE EXCAVATION PROCESS

The simulation of the excavation process is done in Matlab-Simulink and it is applied to excavator EsRc 1400.

The simulation program is based on a mathematical model as determined above.

In the simulation of the excavation process, the dynamic effects introduced by the induction machines that act both the port-cups wheel and the upper platform of the excavator are captured.

The bucket wheel is powered by an induction motor of 630 kW, and the upper platform of the excavator is powered by two 45 kW induction motors.

The induction motors used in the simulation are a squirrel - cage rotor.

The system which puts in motion the bucket wheel of the excavator consists of two sub-systems: the induction motor, the cone - cylinder four gear reducer and the two-speed gearbox.

The system putting in motion of the rotation mechanism of the upper platform consists of two induction motors and two cone-cylinder four gear reducers, identical, one for each motor.

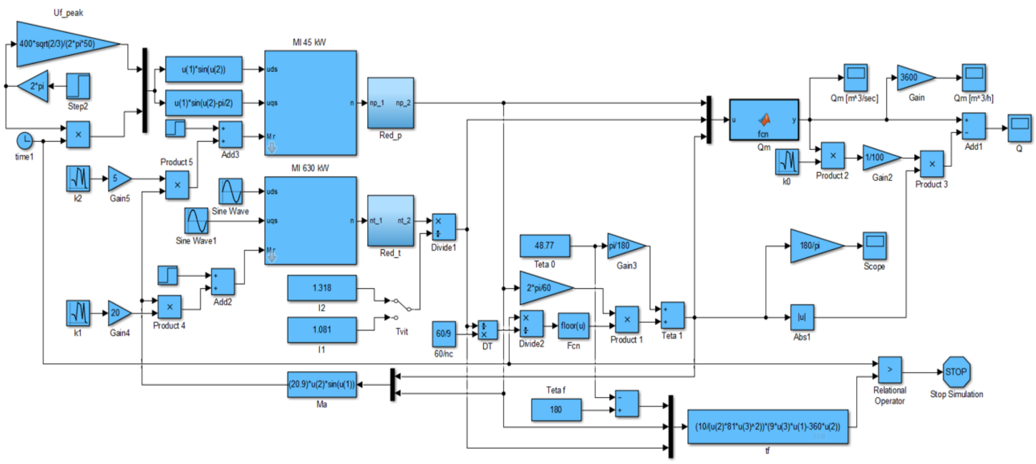

Fig. 3. The program for the simulation of excavation process

The program for the simulation of the coal excavation process with the bucket wheel excavator is presented in Fig. 3.

From Fig. 3, can be seen as within simulation the load torques are directly proportional to the excavation capacity.

To control the slewing speed, a scalar open-loop control system (U/f=ct), is used in the simulation, Stoicuta (2012), Stoicuta (2016). The simulation of the excavation process is done in the case of starting under load of the induction motors. The simulation is done using the Dormand – Prince (ode45) numerical method, imposing a relative and absolute error of $\varepsilon = 10^{-4}$. In the simulation of the scalar open-loop control system, the frequency of the supply voltages of the induction motor of 45 kW, is 25 Hz.

In the analysis of the excavation process by numerical simulation, it will be analyzed 2 pivoting cycles defined by the following initial conditions:

- case 1: $\Theta_0 = 53.09$ [degree] ; $\Theta_f = 180$ [degree] ;
- case 2: $\Theta_0 = 53.09$ [degree] ; $\Theta_f = 138.77$ [degree] ;

The results of the simulation, for cases 1 and 2, in the conditions in which the drive system of the port- cup wheel is operating in stage 1, are shown in the the following figures:

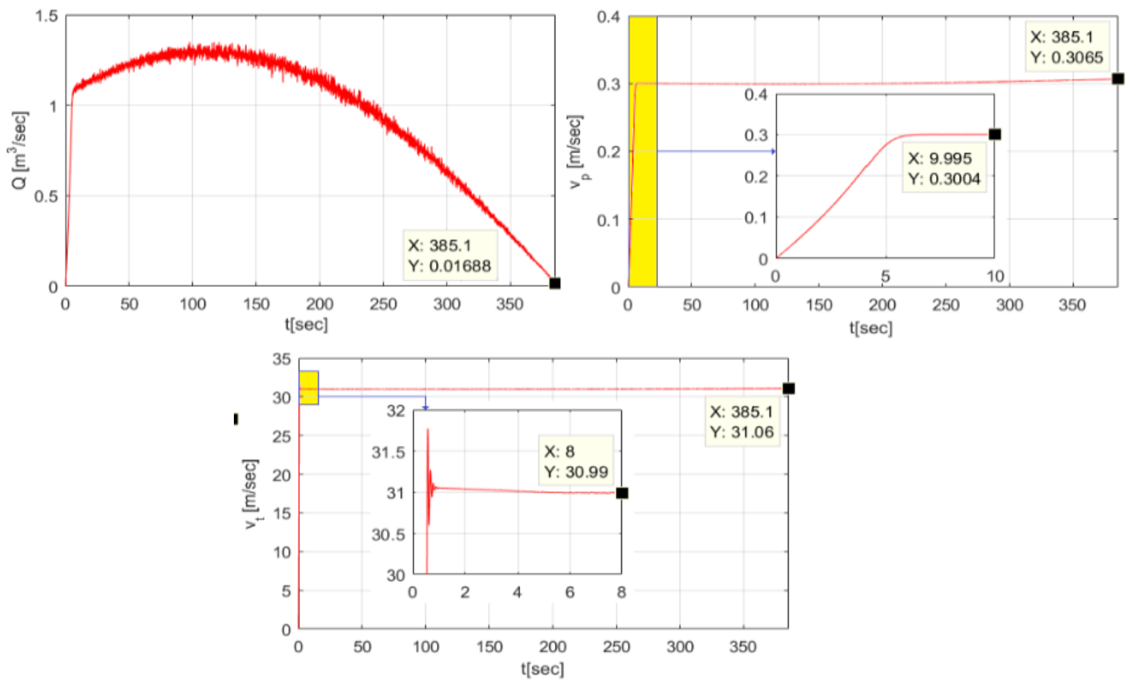

Fig. 4. Time variation of flow rate, pivoting speed and cutting speed case 1 - stage 1

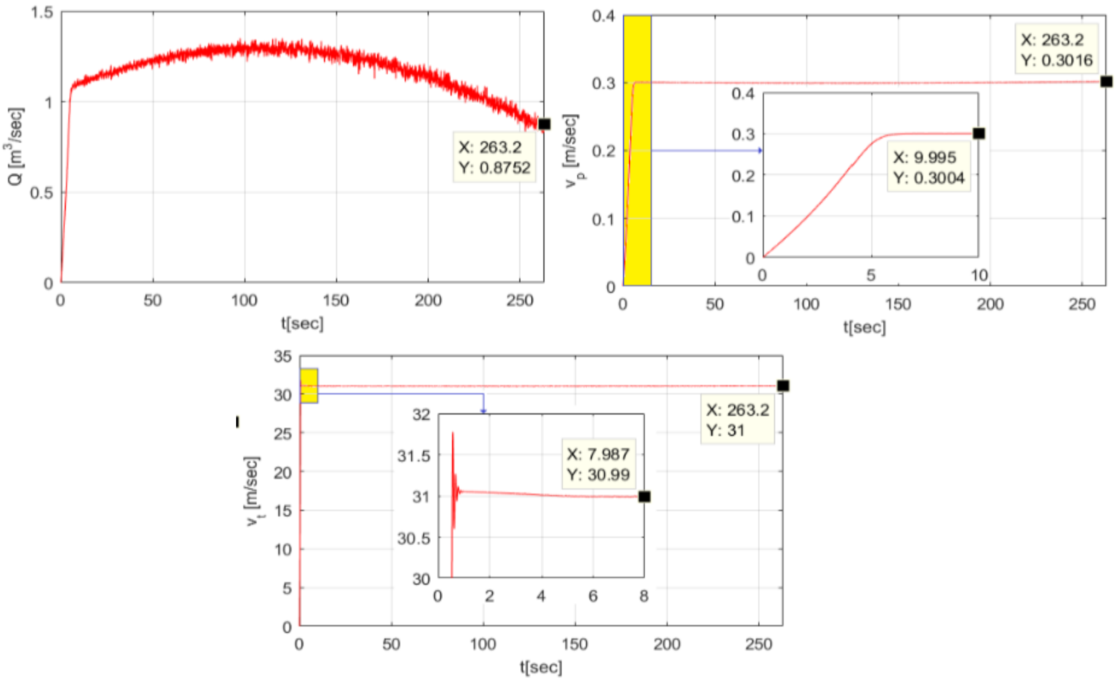

Fig. 5. Time variation of flow rate, pivoting speed and cutting speed case 2 - stage 1

From the figures presented above, it is noted that both in case 1 and 2, the pivoting and cutting speeds are maintained at a constant value throughout the pivot cycle. When the gear shifter in the port-cup wheel is operating in step 1, the steady-state cutting speed is about 31 [m/sec]. On the other hand, the stationary pivoting speeds for both analyzed cases are equal, having a value of approximately 0.3 [m/sec]. From Fig. 4 and Fig. 5, it can be seen that the duration of the pivot cycle for case 1 is approximately 385 [sec] and approximately 263 [sec] for case 2.

Regarding the flow rate of material loaded onto conveyor belt, in both cases analyzed, it is observed that it has a large variation in time, when the pivoting speed is constant.

In conclusion, the realization of relatively constant excavation flow, with as little variation possible within a pivot cycle, can be achieved by the following tandem:

- the total pivot angle is appropriately chosen (has a relatively small value);
- the required pivoting speed is calculated according to the pivot angle based on a control law, that has the role to compensate for variation in the flow time.

4. CONCLUSIONS

From the researches made in this article, an original model of the flow resulting from the excavation process was obtained.

Based on the mathematical model of the flow resulting from the excavation process, a simulation program was developed in Matlab-Simulink, with which two pivoting cycles were analyzed, highlighting the main performance of the excavation process. Simulation of the excavation process was customized on the EsRc 1400 excavator. The simulation in Matlab-Simulink analyzed the excavation process in which the pivoting speed and the cutting speed are kept constant throughout the pivot cycle.

With the simulation programs presented in the article, the optimal values of the cutting parameters can be easily extracted, which allow for a constant amount of flow of material loaded onto the conveyor to be maintained over a certain pivot cycle.

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