Control of the Main Working Axes of Bucket Wheel Excavators According to the Criterion of Desired Capacity

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Abstract—The bucket wheel excavator is basic mining machine used on open pit mines with a continuous excavation process for soft and medium-hard materials. The increase in the need for ever greater quantities of excavated material has led to excavators being constructed today with a daily production capacity greater than 200,000 m$^3$. Aside from the time and capacity availability of the excavators, to achieve efficient production, the manner in which they are controlled is also of great significance. The analysis of the technology for excavating massifs, as well as the structure and geometry of excavators, has led to the greatest number of applied solutions for control of excavators being through automatic operation: $n_p / \cos$ and $P = \text{const}$. Due to the non-homogenous structure of material and the inconsistent and unpredictable geometry of the excavated block, the aforementioned methods do not provide the necessary efficiency for the operation of the excavator.

The development of systems for measuring the volume flow of material and their application on excavators makes it possible for the measurement results to be used not only for statistical analysis, but also to develop algorithms for control of excavators. The location where the measurement system is installed complicates the use of its measurement results. Specifically, the information on the instantaneous production which the control system receives from the measurement system is delayed by the amount of time it takes the excavated material to travel from the bucket wheel to the location where its volume is measured (one of the conveyors on the excavator). In this work we will present the algorithm for control of a bucket wheel excavator according to the criterion of desired capacity, where the results of the system for measuring volume flow are used as feedback information on the capacity. The results of measurements performed on the terrain verify the control strategy, which is developed and tested based on mathematical model of bucket wheel excavator presented in the paper.

Keywords—bucket wheel excavator; control; desired capacity; automatic operation; volume measurement system

I. INTRODUCTION

Excavation of material using a bucket wheel excavator (BWE) is realized using buckets that are equally distributed and fixed to the rim of the bucket wheel (BW). The filling of the buckets of the bucket wheel is achieved through the coordination of three of the excavator’s subsystems:

- Subsystem S1, transport drive, enables horizontal movement of the excavator along the direct axis.
- Subsystem S2, slewing drive, enables rotational movement of the boom together with the upper part of the excavator.
- Subsystem S3, bucket wheel drive, enables rotational movement of the bucket wheel around its axis, in the vertical plane.

During the excavation process, the bucket wheel excavator is located on one of the levels of the surface mine. The section of the level that the excavator excavates through a series of successive and interconnected movements enabled by all three subsystems is called a “block” and encompasses one technological cycle. The geometric characteristics of a block are: block height ($H$), block width ($B$) and block thickness ($T$), as shown in Fig. 1.
All parameters of the block depend on the geometric capabilities of the excavator.

The block is further divided into terraces according to its height. The height of the terraces ($h_g$, where, $g$ represents the number of the terrace counted from top to bottom) depends on the diameter of the bucket wheel ($D$) [1]. Typically, the height of the terrace is, $0.33 - 0.67D$.

Bucket wheel excavators most often excavate the level in horizontal cuts, indicated by the hatching in Fig. 1. As the figure shows, one cut scoops out a volume from the level which is removed by the edges of the buckets of the bucket wheel with one rotation of the boom in just one direction at an angle of, $\beta$ ($\beta_1 = \beta_0$).

Also, in the same figure one can see that the height of the cut is equal to the height of the terrace and the width is equal to that of the block. The thickness of the cut varies according to the law of cosines and its maximum value ($C_0$) is located on the axis of forward movement of the excavator and determined by the horizontal shifting of the excavator which is done before the cut is started.

II. THEORETICAL BASIS FOR CONTROL ACCORDING TO CAPACITY

The capacity of a bucket wheel excavator ($Q [m^3/h]$) is defined as the volume of excavated material over a unit of time. If ($V [m^3]$) is used to signify the volume of material scooped by one bucket during one pass through the material, and ($N_p$) is the number of times the bucket wheel makes a dump within one minute, then the capacity of the excavator is:

$$Q = 60 \cdot N_p \cdot V_0$$ (1)

The number of times a dump is made during one minute is proportionate to the angular speed of the bucket wheel ($n_{sw}[rpm]$) and the number of buckets ($z$):

$$N_p = n_{sw} \cdot z$$ (2)

Taking into account the geometry of the excavator and the shape of the section, shown in Fig. 2, the volume of one section, or rather the quantity of material scooped by one bucket while passing through the material during one full rotation of the bucket wheel equals [2]:

$$dV_0 = b \cdot C_0 \cdot \sin \varphi \cdot \cos \beta \cdot \frac{D}{2} \cdot d\varphi$$ (3)

In the upper equations, ($b$) is the width of the section, ($C_0$) is the length of the excavator’s forward movement during a cut change, ($D$) is the diameter of the bucket wheel, and ($\varphi$) is the angle of rotation of the bucket wheel.

With the condition that the height of the cut (terrace) ($h$) is equal to half of the diameter of the bucket wheel ($D/2$) and an angle ($\varphi$) equal to 90 degrees, we are able to calculate the volume of the section as:

$$V_0 = b \cdot h \cdot C_0 \cdot \cos \beta$$ (4)

The width of the cut ($b$) represents the path which the top of the bucket wheel boom, moving at a slewing speed of ($n_{sw}[rpm]$) strips in the horizontal plane, from the moment one bucket enters into the material to the moment when the next bucket enters into the material. That path depends on the slew radius of the BW center ($R_k$), which, as a parameter of the geometry of the excavator is shown in Fig. 2.

$$b = \frac{2\pi \cdot n_{sw} \cdot R_k}{N_p}$$ (5)

Finally, from the relation of (1) while accounting for relations (4) and (5) for the capacity of the excavator we obtain the following:

$$Q = 60 \cdot 2\pi \cdot R_k \cdot n_{sw} \cdot h \cdot C_0 \cdot \cos \beta$$ (6)

III. MODEL OF A BUCKET WHEEL EXCAVATOR

For the needs of analyzing the operation of an excavator in its entirety and its individual drives, a model of an excavator was developed. Special attention during the development of the model was dedicated to the mechanical parts of the slewing drive of the bucket wheel boom, excavator transport drive and the hoist drive [3, 4]. All of these drives were modeled as multi-motor drives with the electromechanical parts of the drives (from the reference torque to the actual torque) being represented by one block with a short delay [5].

The control subsystem in the model was developed with the aim of enabling analysis of the operation of the excavator with manual operation, programmed operation and automated operation, including the capability of controlling the excavator according to the desired capacity. The principle block diagram of the simulation model of a bucket wheel excavator is shown in Fig. 3.
Verification of the excavator model was achieved by comparing the results obtained through simulation with the measurements taken from a Takraf SRs-1300 bucket wheel excavator. This excavator is in operation on the Open Pit Mine “Drmno” within the structure of the Electric Power Industry of Serbia. An illustration of the considered excavator with its basic parts is shown in Fig. 4.

Fig. 5 shows a comparison of the simulated and measured values on a bucket wheel excavator. The programmed operation mode of the excavator is displayed with a constant bucket wheel speed, depth of cut \( C_0 = 60 \text{[cm]} \) and the slewing speed of the bucket wheel boom varying according to the rule:

\[
n_s = \frac{n_{s0}}{\cos \beta}
\]

where: \( n_{s0}=800 \text{[o/min]} \) is base speed of boom rotation, \( \beta \) is the slewing angle of the boom, with limits (\( \beta_L = -10^\circ \) and \( \beta_R = 100^\circ \)).

The results displayed in Fig. 5 indicate complete quantitative and qualitative concurrence of the technological values (angle and depth of cut) and the speed. The curve of the measured and simulated capacities correspond to one another qualitatively, while a certain degree of quantitative deviation occurs due to the impossibility of recognizing all parameters of the configuration of the levels on which the excavator excavates.

The appearance of the curve of the depth of cut is the result of the manner in which the control algorithm was realized on the excavator. The measured value of the depth of cut resets when the angle of rotation of the boom is equal to half of the value of the sum of the borderline angles. The same solution was implemented within the model.

IV. CONTROL ACCORDING TO DESIRED CAPACITY

Today, modern systems for measuring the volume flow of materials are mostly installed on bucket wheel excavators. In a majority of cases, the results of those measurements are used exclusively for monitoring the statistical production of the excavator, but this knowledge can be better utilized to provide feedback to mine planning and scheduling [6].

Relation (6) shows that through control of the slewing speed of the bucket wheel boom \( (n_s) \) it is possible to achieve the desired capacity. The depth of the cut \( (C_0) \) and height of the cut \( (h) \) for one cut are constant. This means that the reference slewing speed \( (n'_s) \) of the boom must be an output of any control algorithm according to the desired capacity. The input value for such an algorithm is the desired capacity. The problem in the realization of the control algorithm is the feedback for which the measured capacity should be used.

The system for measuring the capacity is placed on the end of bucket wheel conveyor, which is the first in the series of the excavator conveyors that carry away the excavated material. Because of this, the information on the measured capacity is delayed by the time interval necessary for the excavated material to travel from the bucket wheel to the location where the measurement system is installed. Fig. 6 shows the measurement results from the excavator that illustrate this fact.

The measurement result of the angle of rotation of the bucket wheel boom \( (\beta) \) is expressed in degrees. The depth of cut \( (C_0) \), before each cut is started, is expressed in \([\text{cm}]\). The
torque of the bucket wheel drive ($T_{w}$) is expressed in [\%]. A value of 100[\%] corresponds to the rated torque of the bucket wheel motor. The measurement capacity is also expressed in percentages. A value of 100[\%] corresponds to the theorectic capacity of this excavator of 4200 [m$^3$/h].

Observing the middle and lower diagram in Fig. 6, one can see there is a qualitative and quantitative interdependency between the torque of the bucket wheel motor and the capacity of the excavator, especially in the lower diagram which displays the filtered values of torque and capacity. In that diagram, the curve of the capacity is shifted on the time axis towards the left by the amount of time necessary for the excavated material to travel from the bucket wheel to the capacity measurement system.

Fig. 7 provides a functional dependency of the bucket wheel motor torque of the capacity in the case of time diagrams shown in Fig. 6. The same diagram also shows a linear regression line for the displayed points.

The existence of the clear dependency of the bucket wheel load torque on the excavator capacity is the basis for one solution for the automatic operation of the excavator, i.e. the operation with a constant power ($P_{c}$=const). The idea to assign a corresponding (desired) load to achieve operation of the excavator with the corresponding (desired) capacity is not realistically achievable. A large number of factors affect this dependency, so any specific load on the bucket wheel drive corresponds to a new value for the excavator capacity.

![Fig. 7. Bucket wheel motor torque in the function of capacity](image)

The characteristics of the material (hardness, composition, etc.) that is being excavated, the quality of the cutting elements on the buckets of the bucket wheel, the shape of the buckets and the resistances of motion on the bucket wheel drive are just a few of the numerous factors that determine the dependency of the (load) torque of the bucket wheel drive and excavator capacity and therefore influence the control according to desired capacity [7].

Another solution for automatic excavator operation is where the speed of rotation of the bucket wheel boom varies with a reciprocal value of the cosine of the bucket wheel boom rotation angle, $n_{w}/\cos\beta$. This operation is described as operation with a constant capacity which is valid only when excavating homogenous materials. This is achieved thanks to the fact that the change in slew speed according to the rule given in expression (7) compensates for the change in thickness of the cut in the function of the angle of rotation ($\beta$). The shortcomings of this type of automatic operation are: 1) excavated material is most often not homogenous, so the capacity of the excavator changes during excavation of one cut, 2) the reference capacity can be obtained only with proper selection of the basic speed ($n_{b}$), otherwise a capacity is achieved that is different from the reference. From the aforementioned, it can be concluded that the most commonly applied solutions for automatic excavator operation do not provide control of its basic result of operation, capacity.

Further on in this work, descriptions will be provided for the algorithm for control of an excavator according to capacity based on the measured capacity, results of the application of the algorithm on a simulation model and the measurement results from a SRs 1300 excavator during the operation with the considered algorithm.

A block diagram of the proposed algorithm for control of the excavator according to capacity is displayed in Fig. 8. In the part of the algorithm based on the known geometry of the excavator ($R_{b}$), parameters of the excavator rotation drive ($n_{b}$), and the desired capacity ($Q_{d}$), the depth of cut is calculated ($C_{b}$). The maximum value for the depth of cut is limited by the bucket depth. In this calculation, half ($C=0.5$) of the rated slewing speed ($n_{w}$) is adopted so that the capacity regulator would have sufficient reserves to achieve the desired capacity by changing the slewing speed.

The excavator cut depth is also affected by the height of the terrace ($h_{t}$). The height of the highest terrace ($g=1$) is entered in by the excavator operator through SCADA, which is a part of the control system on the excavator. The heights of the remaining terraces ($g=2, 3...$) are calculated on the basis of the measurement from the hoist drive. On the SRs 1300 excavator, by measuring the drum rotation speed for winding of the winch cable of the bucket wheel boom, the change in the length of the cable ($\Delta l$) is calculated. From this value and the generated nonlinear function for the specific excavator construction, the heights of the remaining terraces ($h_{tg}$, for $g=2, 3...$) are calculated. Another often applied solution is measurement using an absolute encoder installed in the rotation axis of the bucket wheel boom.

The middle part of the proposed control algorithm consists of the capacity regulator. The output value of the regulator is the reference slewing speed ($n_{s}$) of the bucket wheel boom, which is limited by the rated speed ($n_{b}$). The input for the regulator is the difference between the reference ($T_{w}$) and actual ($T_{w}$) torque of the bucket wheel motor. Previous analysis showed that the actual value of the bucket wheel motor torque depends on the instantaneous capacity of the excavator under certain operating conditions.

The reference value of the bucket wheel torque ($T_{w}$) represents the sum of two components. The first component ($T'$) is the output value of the functional dependency of the bucket wheel torque on the capacity. This functional dependency is initially determined at the time of implementation of the control algorithm based on the measurements on the excavator, according to the described method presented in Fig. 7. The second component ($T_{c}$) represents the correction of the reference torque.

This component represents the response of the control system to changes in excavation conditions. The value of the torque correction is constant during one cut and changes during periods when the absolute value of the slewing angle of the bucket wheel boom ($\beta$) is greater than the value of the assigned borderline angles ($\beta_{l}$ and $\beta_{L}$). The overshot of the slewing angle is the result of the high total inertia of the slewing drive, including the upper structure of the excavator (boom, platform, ...).
The value of the torque correction ($T_k^*$) is obtained by integrating the difference between the values of the desired capacity ($Q^*$) and the mean value of the achieved capacity ($Q_{AV}$). The mean value of the achieved capacity is calculated from the instantaneous values of capacity over the duration of the cut. In this calculation, only the values of instantaneous capacity greater than 70% ($C_1=0.7$) of the desired capacity ($Q^*$) are taken into account. The desired capacity ($Q^*$) and the values of the borderline angles of the excavator rotation ($\beta_L$ and $\beta_R$) are entered in through SCADA by the excavator operator.

V. RESULTS OF THE APPLICATION OF CONTROL ACCORDING TO DESIRED CAPACITY

The results of the algorithm for control according to desired capacity obtained from the excavator simulation model are shown in Fig. 9. The assigned value of reference capacity is $Q^*=2000\text{ m}^3/\text{h}$, with values of borderline angles $\beta_L=10^\circ$ and $\beta_R=80^\circ$. Operation of the excavator in non-homogenous material was simulated.

Curve ($h$) in the upper diagram displays the form of the non-homogenous material. The coordinate system for this curve is shifted along the Y axis by $-100$. The value of the curve represents the height of the terrace in the simulation in [dm].

The upper diagram also shows the simulated values of the angle ($\beta^*$), depth of cut ($C$[dm]) and slewing speed ($n[\%]$) in percentages of the rated slewing speed. From the speed graph one can see the reaction of the algorithm for control according to capacity on the existing non-homogeneity in the material.

Fig. 8. Block diagram of control algorithm according to desired capacity

Fig. 9. Simulation of excavator operation with application of algorithm for control according to desired capacity
The middle diagram shows the percentage values of the desired \( Q^* \) and calculated \( Q \) capacity and its mean value \( \langle Q_{av} \rangle \) during one cut. All of these values are displayed in percentages. Values of 100% correspond to the theoretical value which corresponds to the reference torque of the bucket wheel \( T_{BW} \). The indicated details of these values from Fig. 9. are shown in Fig. 10. The proportions on these diagrams were selected so that they clearly illustrate the effect of the deviation of the mean value of capacity \( \langle Q_{av} \rangle \) from the desired capacity \( Q^* \). The indication of the change in value of the reference torque of the bucket wheel \( T_{BW} \).

![Diagram showing percentage values](image)

Fig. 10. Detail of change of reference torque of bucket wheel in the function of the difference between achieved mean and desired capacity.

The Fig.11 shows results of measurements performed on the excavator during the operation with control algorithm according to the criterion of desired capacity.

![Diagram showing measurements](image)

Fig. 11. Display of measurements from the excavator operation with application of algorithm for control according to desired capacity.

**VI. CONCLUSION**

The size and complexity of bucket wheel excavators implies significant investment and operational expenses. Because of this, it is of particular interest to investigate systems for control of an excavator as a whole, as well as the automation of its operation. The results presented in the paper provide a contribution to that research.

Analyses of results of measurements and results of simulations of the developed mathematical model of an excavator confirm its accuracy. This guarantees that the model represents a good basis for further research. The excavator model, aside from the presented review of the methods for control, may also be used in analyses of its operation and the control of individual subsystems (drives) of the excavator, which was not elaborated on in the paper.

The measurement results from the excavator where the proposed control algorithm was implemented confirm its applicability. Furthermore, the performance results of the excavator obtained since the implementation of the algorithm prove the feasibility of introducing a new method for control. The simplicity of application for the operator represents a significant advantage in conditions where operation of an excavator with a specific capacity is required. The requests from users for implementation of such a method for control on other bucket wheel excavators located in the same open pit mine are the greatest testament to the success of the entire idea.

**TABLE I. TECHNICAL DATA OF BWE SRS 1300 26/5+VR**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>BW diameter</td>
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<tr>
<td>BW drive power</td>
<td>[kW]</td>
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</tr>
<tr>
<td>Theoretical output</td>
<td>[m³/h]</td>
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<td>Digging height ((H))</td>
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<tr>
<td>Slew radius of BW centre</td>
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<td>Installed motor power</td>
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<td>Conveyor belts width</td>
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<td>Travel drive power (6 pcs.)</td>
<td>[kW]</td>
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<tr>
<td>Slewing drive power (3 pcs.)</td>
<td>[kW]</td>
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</tr>
<tr>
<td>Hoist drive power (2 pcs.)</td>
<td>[kW]</td>
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**REFERENCES**


