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Efficiency increase in excavation control as primary reserve of performance increase for open-pit excavators

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Abstract. It is shown that controlling excavation of rock mass using an open-pit excavator with a front shovel as its operational equipment is quite a difficult task due to the complexity of control under almost nonstop adjustment of velocities of working motions (hoisting and thrusting). It was established that operation parameters of the main mechanisms depend on the type of path of motion and position of the bucket in the excavator's work area. The process of excavation was algorithmically described, and kinematic transfer functions for the operational equipment mechanism were determined, characterizing correlations between the velocity of excavation and the velocities of working motions.

1 Introduction

Open-pit excavators are the main type of excavation-and-loading machinery used in open pits.

Bearing in mind the current situation of limited material and energy resources, it is now paramount to increase the technical level of technological equipment and develop high-production, resource-saving machinery.

The solution of this problem could be based on a complex approach which would utilize the results of scientific research obtained both from engineering science and studies of the processes which are inherent in the operation of technological machines.

Analysis of publications on open-pit excavators [1-8] showed that those are mainly concerned with finding new technical solutions, modeling operating process-es, automating and robotizing machinery, and optimizing equipment parameters.

On the other hand, the problems of forming operational characteristics of the main mechanisms of excavators, their role in defining energy-force parameters of the working process of excavation and, in general, the quality of control and efficiency of operation have not been covered enough for open-pit excavators.

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2 The goal of the research and its tasks

The goal of the research is to increase efficiency of operation for open-pit excavators in the process of rock mass excavation.
The tasks of the research are:
- to define kinematic transfer functions of the operational equipment mechanism while the bucket is moved within an excavator's work area;
- to determine the range of variation for operation parameters of the main mechanisms in the process of rock mass excavation.

3 The solution of the tasks

The object of the research is the working process of excavation, which is carried out using the operational equipment of an open-pit excavator of the front-shovel (mechanical shovel) type.

The subject of the research consists in determining correlations between energy-force parameters, realized on the cutting edge of bucket teeth, and operation parameters of the main mechanisms.

The methods used in the research are those of mathematical modeling of the operational equipment, simulation modeling of the process of excavation, and a computing experiment aimed at finding operation parameters of the main mechanisms during excavation.

The process of excavation – which involves moving the bucket up to the maximal height of excavation while separating the upper layer of rock mass («chips») and filling the bucket – is characterized by interaction between the main (hoisting and thrusting) mechanisms and the operational equipment mechanism, which connects the main mechanisms with the bucket (Fig. 1). Considering this case, one could note that the bucket is in fact a driving link (both in relation to the operational equipment mechanism and the main mechanisms), and the output links of the main mechanisms become driven members, that is, in the process of excavation, «reversibility» of the main mechanisms occurs. Then, the operation parameters of the main mechanisms could be determined on the basis of the path of bucket motion (the top of cutting edge) and position of the bucket within the excavator's work area, and also would depend on kinematic properties of the operational equipment.

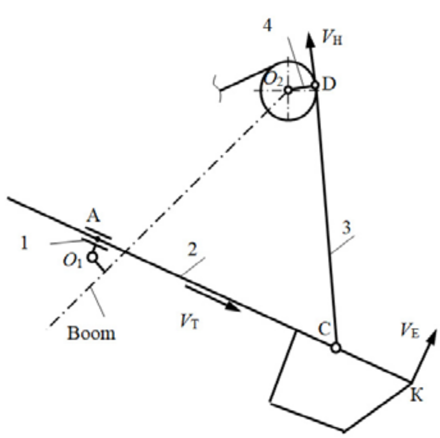

Fig. 1. Schematics of the operational equipment mechanism: 1, 4 – cranks; 2 – stick with bucket; 3 – hoisting rope; V_H, V_T, V_E – velocities of hoisting, thrusting and excavation

All in all, variation of the velocities of the working motions in the process of excavation could be defined by kinematic properties of a two-crank leverage mechanism of the operational equipment.

The kinematic analysis of the two-crank leverage mechanism of the operational equipment provided the expressions for the kinematic transfer functions (thrusting mechanism – $f_T = \frac{V_T}{V_E}$ and hoisting mechanism – $f_H = \frac{V_H}{V_E}$) which determine the required ratios between the velocity of excavation V_E and the velocities of hoisting V_H and thrusting V_T in the process of excavation.

It was established that the type of a kinematic transfer function depends on the position of the stick-bucket (bucket) link in the work area of an excavator:
- when the bucket is located in the bottom section of the work area of the excavator, the function f_T is negative;
- when the bucket is located in the middle section, the functions f_H and f_T are positive;
- when the bucket is located in the upper section, the function f_H is negative.

The expressions for determining the kinematic transfer functions take the following forms:
- when the bucket is located in the bottom section of the work area ($\varphi_1 + 90° < \psi$)

$$f_{T1} = -\frac{\cos(\psi - \varphi_1)}{\sin(\alpha - \varphi_1)},$$

$$f_{H1} = \sin(\varphi_2 + \varepsilon + \delta - \gamma)\sqrt{f_{T1}^2 + a^2 + 2af_{T1}\cos(\alpha - \varphi_2)};$$

- when the bucket is located in the middle section ($\varphi_1 + 90° > \psi$)

$$f_{\mathrm{T2}} = -\frac{\cos(\psi - \varphi_1)}{\sin(\alpha - \varphi_1)},$$

$$f_{\mathrm{H2}} = \sin(\varphi_2 - \varepsilon + \delta - \gamma)\sqrt{f_{\mathrm{T2}}^2 + a^2 - 2af_{\mathrm{T2}}\cos(\alpha - \varphi_2)};$$

when the bucket is located in the upper section ($\gamma - \delta \geq \varphi_2 - \varepsilon$)

$$f_{\mathrm{T3}} = f_{\mathrm{T2}},$$

$$f_{\mathrm{H3}} = \sin(-\varphi_2 + \varepsilon - \delta + \gamma)\sqrt{f_{\mathrm{T3}}^2 + a^2 - 2af_{\mathrm{T3}}\cos(\alpha - \varphi_2)},$$

where $a = \frac{O_1C\cos(\psi - \alpha)}{O_1K\sin(\alpha - \varphi_1)}$; O_1C, O_1K are radius vectors of points C and K; α, γ, δ, φ_1, φ_2 are angles which determine the positions of the links; ψ is angle of the tangent to the path of bucket motion (point K – the top of cutting edge).

To solve other tasks of the research, simulation modeling – based on a mathematical model of the operational equipment mechanism [9] – was run on the process of excavation.

Modeling excavation using specified values of the parameters determining the position of the bucket in the work area of the excavator (coordinates of its cutting-edge top, velocity of excavation, angle of the tangent to the path of bucket (cutting-edge top) motion, etc.) helps to evaluate the operation parameters of the main mechanisms [10].

In a general form, the results of simulation modeling represent functionals – dependencies between calculated energy-force parameters realized on the bucket at a specified point (or region) of the work area and appropriate operation parameters of the main mechanisms and drives.

Figures 2 and 3 shows graphs relating hoisting and thrusting velocities to the height of excavation while the bucket is moved within the work area of an excavator following equidistant paths – initial, intermediate or terminate. Calculated velocities of hoisting and thrusting were determined with the help of a computing experiment run for the EKG-20A excavator made by JSC «Uralmashplant» [11-13].

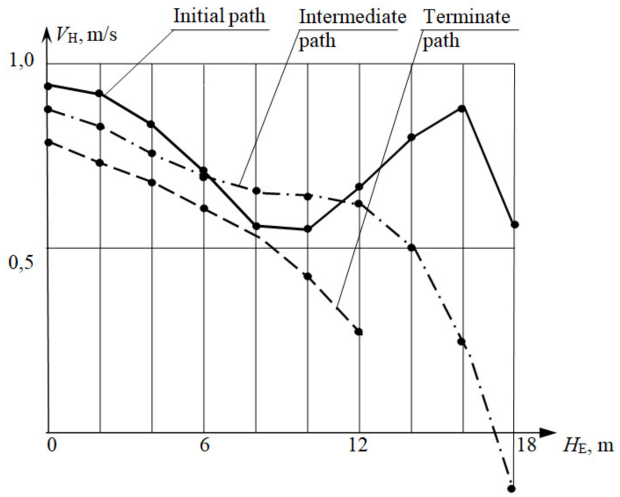

Fig. 2. Graphs relating the hoisting velocity to the excavation height for a bucket moving along equidistant paths (excavation velocity V_E = 1 m/s)

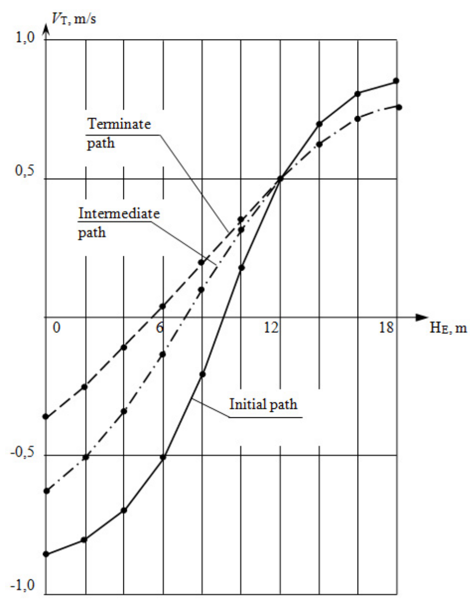

Fig. 3. Graphs relating the thrusting velocity to the excavation height for a bucket moving along equidistant paths (excavation velocity V_E = 1 m/s)

The data obtained leads to the conclusion that the velocities of working motions depend both on the height of excavation and the type of motion path for the bucket (its cutting-edge top).

For example, the velocity of hoisting decreases with the rise of excavation height, but for the initial path of bucket motion that decrease is only true in the bottom section, and for the intermediate path of motion it becomes negative at the maximal height of excavation.

The velocity of thrusting increases with the rise of height – from negative values when the stick is retrieved into the saddle bearing to positive ones when it is extended.

Thus, in the process of rock mass excavation, the operation parameters of the hoisting and thrusting mechanisms are converted in accordance with the kinematic properties of the leverage mechanism of the operational equipment.

As a result, the operation modes of the drives of the main mechanisms and the hoisting and thrusting velocities and forces change, impeding the process of excavation.

In general, achieving effective control over the process of excavation and providing the required law of bucket motion is only possible when the position of the bucket in the pit is controlled in an almost nonstop fashion, and the velocities of the working motions are constantly adjusted.

4 Conclusion

Development and introduction of a PC-based control system for the drives of the actuating mechanisms on the basis of calculated (computed) values of the hoisting and thrusting velocities could allow to realize almost any path of bucket motion due to having the motions of hoisting and thrusting coordinated during the process.

Assessing kinematic properties of a two-crank leverage mechanism of the operational equipment would help to develop such an algorithm for controlling the drives of the main mechanisms working jointly during rock mass excavation which could realize rational values of the operation parameters of the main mechanisms for specific mining and technical operational conditions.

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