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Evaluation of Single-Bucket Excavators Energy Consumption

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Abstract

It is shown that with the increase in capacity and weight of excavators their specific indices of functioning remain practically at the same level corresponding to the energy consumption value (available power) for excavators of each type (electromechanical or hydraulic). That value depends on the type of operational equipment, the ratio between linear and weight parameters and other factors. New layout of the operational equipment is suggested, featuring an internal closure of workloads within its operating element. The layout includes the operating element in the form of two oppositely arranged buckets and the closure mechanism. Energy efficiency index for single-bucket excavators is proposed.

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Keywords: single-bucket excavators; specific indices; internal closure of workloads; energy efficiency.

1. Overview of the problem

The main direction in the development of productive forces is the creation of high-performance and resource-saving machines of new generation.

The technical level of single-bucket excavators is characterized by specific (correlated with the weight of a machine) values of its principal indices – installed capacity of driving motors (motor capacity) and bucket capacity.

Real-life designing and usage of single-bucket excavators shows that with the increase in performance and weight their specific indices and, in general, operational efficiency remain practically the same.

This fact is due to one specific feature of their force diagram (the diagram of reception and closure of external loads). In traditional designs of excavators the workload (rock resistance to digging), the terminal load (gravitational

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force of the loaded bucket) and the gravitational force of operational equipment are all received by their metalwork, then transmitted to their undercarriage and closed by the ground reaction. At the same time, the total tilting moment applied to the excavator is balanced by the total moment of confining forces (gravitational forces of the turntable, counterweight and undercarriage).

As a result, with such a force diagram, the calculation of the terminal load, the bucket capacity and the motor capacity depends on the weight of an excavator.

2. Formulation of the problem

A fundamental solution to the problem of improving the technical level of single-bucket excavators could be achieved by means of changing the force diagram of a machine.

It is known [1] that the force diagram is efficient if external loads close within a short segment by elements working, preferably, in tension or compression. This research aims at improving the efficiency of excavators. This goal is achieved through the development, on the basis of an efficient force diagram, of such operational equipment which would provide the closure of the workload.

In such a case, the exclusion of the workload's tilting moment, with its impact on the excavator, leads to the increase of the terminal load (the bucket capacity) and, therefore, of the performance, with the weight of the excavator unchanged.

The main objectives of the research are:

- to validate the proposed layout diagram for the operational equipment with the closure of the workload;
- to determine the main indices of the excavator with the efficient force diagram and to assess its energy consumption level.

3. The results

In this paper the technical level of electromechanical (shovels) and hydraulic excavators is estimated by comparing specific values of its main indices.

Table. 1 shows technical characteristics of excavators.

The specific bucket capacity e, the specific motor capacity p and the stability index I_{st} are determined as:

$$e = \frac{E}{M};\ p = \frac{P_{inst}}{M};\ I_{st} = \frac{M}{ER_{d\,max}}, \qquad (1)$$

where E – the bucket capacity; M – the excavator mass; P_{inst} – the motor capacity; $R_{d\,max}$ – the maximum digging reach.

The specific bucket capacities are:

- for shovels made in Russia $e_m = 0,018 \ldots 0,022$ m^3/t;

- for hydraulic excavators (except EG-20) $e_{EG} = 0,050 \ldots 0,063$ m^3/t.

The specific motor capacities are:

- for shovels $P_m = 1,86 \ldots 2,20$ kW/t;

- for hydraulic excavators (except EG-20) $P_{EG} = 3,63 \ldots 4,53$ kW/t.

The stability indices are:

- for shovels made in Russia $I_{st.m} = 1,86 \ldots 2,09$;

- for hydraulic excavators $I_{st.EG} = 1,86 \ldots 2,09$.

Table 1. Technical characteristics of mechanical shovels and hydraulic excavators [2-4].

Indices	Shovels					Hydraulic excavators					
	(1) EKG-12	(1) EKG-20	(2) EKG-15	(3) 2300XPC	(3) 2800XPC	(1) EG-20	(2) EG-110	(4) PC1250	(4) PC2000	(5) R995	(5) R9800
Bucket capacity, [m^3]	12	20	15	25,5	35,7	20	5,5	6,5	11	28	42
Maximum digging reach, [m]	21	23,4	22,6	21,3	24,2	19	9,9	11,4	13,2	17,8	20,1
The load on the bucket's suspension (penetration load), [кH]	1225	2000	1470			(2000)	(390)				
Terminal load, [kN]				907	1180						
Motor capacity [kW]	1250	2250	1250	2000	2500	1260	450	485	728	1600	2984
Working mass, [t]	655	1075	672	911	1310	570	110	107	195	441	793
Stability index	2,60	2,30	1,98	1,68 (0,047)*	1,52 (0,046)	1,50	2,02	1,88	1,34	0,89	0,94
Specific motor capacity	1,91	2,09	1,86	2,20	1,91	2,21	4,09	4,53	3,73	3,63	3,76
Specific bucket capacity	0,018	0,019	0,022	0,028	0,027	0,035	0,050	0,061	0,056	0,063	0,053

* evaluated by terminal load

Manufacturers are: 1 – JSC «Uralmashplant»; 2 – LLC «IZ-KARTEX»; 3 – P&H Mining Equipment (USA); 4 – KOMATSU (Japan); 5 – LIEBHERR (Germany).

The validity of the performed assessment is confirmed by a minimal spread of values of the specific indices for excavators made by one company. On the whole, the calculated values of the specific indices for hydraulic excavators significantly (2 – 3 times) exceed those for shovels, and the values of their stability index are significantly less than the ones of shovels [5].

The increase of values of the specific indices for hydraulic excavators is due to their ability to use various modes of operation – both digging and penetration of the bucket into the broken rock are available, all owing to the high kinematic mobility of their operational equipment. When the bucket penetrate almost horizontally into the broken rock, the tilting moment of the workload is excluded and, accordingly, the value of the total moment of confining forces (the mass of the excavator) decreases.

In such a case, the maximum values of the bucket capacity and the terminal load are determined on the condition of the excavator's stability during the transportation of its loaded bucket.

This condition is represented as following:

$$M_{conf} = M_{tilt} k_{st} = (G_{eq} R_{eq} + G_{b+r} R_{ter}) k_{st}, \qquad (2)$$

where M_{conf} и M_{tilt} – the total moments of confining and tilting forces; G_{eq} – the gravitational force of the operational equipment (without the bucket); G_{b+r} – the terminal load; R_{eq}, R_{ter} – moment arms; k_{st} – the stability coefficient.

Also, the value of the workload (the penetration force F_{pen}), determined on the condition of traction between the undercarriage (crawlers) and the ground, increases significantly to $F_{pen} = (0,3 \ldots 0,5)G$, where G is the gravitational force of the excavator.

The increase of the workload during the penetration of the bucket, caused mainly by the increase in energy intensity while excavating the rock and penetrating (forcing through) into it with the bucket, leads to a significant increase in energy inputs [6,7], with the load and mass of the operational equipment also on the rise.

Thus, the workload boost of the penetration provides an essential increase of the bucket capacity and a decrease of the metal content of the excavator. At the same time, the energy consumption and the motor capacity significantly increase. Besides, implementation of the penetration mode requires quality preparation (loosening) of the rock.

On the whole, the main operational mode of hydraulic excavators processing the bottom of the mine's operational zone is the digging. During that processing stage, either in the penetration or digging mode, the weighted average value of the power consumption is virtually equal to the power consumption of the digging mode, and, therefore, the efficient value of the specific motor capacity for hydraulic excavators, on the condition of the full usage of their motor capacity, should be considered equal to the specific motor capacity for shovels (as in the excavators EKG-20 and EG-20).

Thus, the efficient level of the energy consumption for single-bucket excavators, equated with the specific value of the motor capacity for shovels, is $E_{sbe} = 1,86...2,20 \; kW/t$.

All in all, the increase of the technical level of hydraulic excavators, which is manifested by the significant increase of the specific bucket capacity (2,5 – 3 times) and, accordingly, by the decrease of the metal content of the excavator, is provided by the exclusion of the workload's tilting moment and, at the same time, by the decrease of the confining force's moment. However, in such a case, the level of the energy consumption increases (2 … 2,5 times), and so do the load and the mass of the operational equipment.

A new layout diagram of the hydraulic excavator's operational equipment, which provides the closure of the workload within the operating element and helps to exclude the workload's tilting moment [8], was developed by the Department of mining machines and systems of the URSMU (Ural State Mining University). The operational equipment consists of the operating element with two oppositely arranged buckets and the closure mechanism. Figure 1 shows the diagram of the operating element; the main element of the operational equipment is the closure mechanism, which implements the following functions – the rock's excavation, the operating element's loading and its unloading.

The replacement of the existing means which realize those functions in standard layouts of the operational equipment (hydraulic cylinders which rotate the boom, the arm or the bucket) by the closure mechanism provides a significant increase in the usage efficiency of the power equipment's installed capacity and in the quality of the operational control.

At the closure of the buckets the force of the operating element's resistance to digging is equal to the force of one bucket's resistance to digging, i.e. the relative digging force (correlated with the operating element's capacity) decreases twofold, and, accordingly, the load and mass of the operating element decrease as well. Finally and similarly, the energy intensity of the excavating process decreases twofold.

The operational equipment with the closure of the workload allows to implement a fundamentally new method of excavation which is based on the intake of the mined rock by the closure of the buckets both above and below the datum level. The operability of the proposed layout was confirmed by its bench-testing.

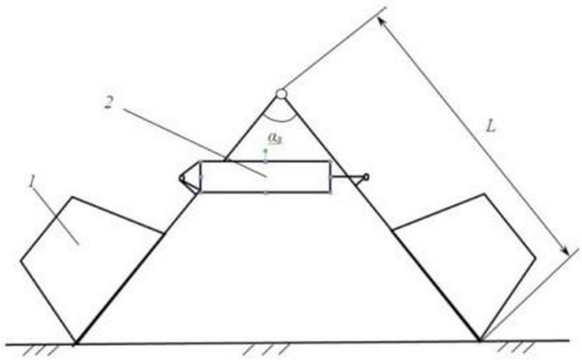

Fig. 1 – Layout diagram of the operating element with the closure of workloads (1 – bucket; 2 – closing hydraulic cylinder)

The maximum value of the operating element's load capacity is determined on the condition of the excavator's stability during the transportation of the loaded bucket (as is with the hydraulic excavator's bucket capacity in the penetration mode), and thus is calculated as $E_{cmax} = e_{EG} M$.

Also, some analytic dependences, which could be used to evaluate the basic parameters of the excavator with the workload's closure, has been obtained

The load capacity of the operating element, determined by the volume V of the rock taken in as a result of the buckets' closure, is evaluated as

$$E_c = VK_E^{-1}, \tag{3}$$

where $V = SB_b$; $K_E = K_L/B_S$; $S = 0,5L^2 (\alpha_c - sin\alpha_c)$ – the area of the circular segment; L – the length of the bucket's arm; α_c – the angle of the closure; B_b – the bucket width; K_E – the excavation coefficient; K_L – the load coefficient for the operating element; K_S – the loosening coefficient for the rock in the bucket.

The motor capacity is determined by the following dependence:

$$P_{inst} = E_{cmax} a_c t_c^{-1}, \tag{4}$$

where a_c – the energy intensity of operation at the closure of the buckets; t_c – the duration of the closure.

The energy intensity of operation at the closure of the buckets is determined as [9]

$$a_c = K_1 \left[\alpha_c + 2cos\frac{\alpha_c}{2} ln\, tg\left(\frac{\pi - \alpha_c}{4}\right)\right]\left(\alpha_c - sin\alpha_c\right)^{-1}, \tag{5}$$

where K_1 is the coefficient of the rock's resistance to digging.

At the angles of the closure $\alpha_c = 90 – 120°$ the energy intensity $a_c = (0,57...0,63)K_1$.

The duration of the closure is calculated as $t_c = 0,5L\alpha_c V_c^{-1}$, where L – the length of the bucket's arm; V_c – the rate of the closure.

The main indices for the EGZ excavator with the closure of the workload within the operating element have been calculated using the reference data for the R995 excavator:

$$E_c = 28\ m^3;\ M = 441\ t;\ \alpha_c = 90°;\ B_b = 1,4\sqrt[3]{0,5E_c} = 3,4\ \ m;\ V_c = 0,5\ \ m{\cdot}s^{-1};$$

$$K_L = 1;\ K_S = 1,35;\ \ K_1 = 325\ \ kPa;\ e_{EG} = 0,063\ m^3/t;\ a_c = 0,57K_1.$$

4. The results of the calculation of the EGZ excavator's parameters

The volume of the rock V which is taken in at the buckets' closure is $V = E_c K_c = 28 \cdot 0,74 = 20,7\ \ m^3$.

The length of the bucket's arm: $L = \sqrt{\dfrac{2V}{B_b(\alpha_c - sin\alpha_c)}} = \sqrt{\dfrac{2 \cdot 20,7}{3,4 \cdot (1,57 - 1)}} = 4,6\ \ m.$

The duration of the closure $t_c = 0,5L\alpha_c V_c^{-1} = 0,5 \cdot 4,6 \cdot \dfrac{1,57}{0,5} = 7,2\ \ s.$

The motor capacity $P_{inst.c} = E_c a_c t_c^{-1} = 28 \cdot 0,57 \cdot 325 \cdot 7,2^{-1} = 720\ \ kW.$

The specific motor capacity $P_c = \frac{P_{inst.c}}{M_c} = \frac{720}{441} = 1,63\ kW/t.$

The technical level of different types of excavators (shovels and hydraulic excavators with the standard operational equipment and the equipment with the closure of the workload) has been assessed (Table 2).

Table 2. Technical characteristics (and calculation data) for a shovel, a hydraulic excavator and an excavator with the closure of the workload

Indices	2300XPC	R995	EGZ
Bucket capacity, [m^3]	25,5	28	28
Motor capacity, [kW]	2000	1600	720
Working mass, [t]	911	441	441
Specific motor capacity	2,20	3,63	1,63
Specific capacity of the bucket (the operating element)	0,028	0,063	0,063
Energy efficiency, [m^3/kW]	0,013	0,018	0,039

For the assessment of the excavator's energy consumption level the index of the energy efficiency is proposed as

$$I_{EE} = \frac{E}{P_{inst}}.$$

This index describes the level of performance for excavators with energy inputs of the given value.

The above table demonstrates that the EGZ excavator with the closure of the workload is notable for its maximum value of the energy efficiency index, i.e. more effective usage of the energy resources is provided.

Conclusion

The levels of energy consumption for different types of single-bucket excavators (electromechanical (shovels) and hydraulic) have been determined.

It has been shown that the energy consumption level depends on the excavator's force diagram type.

An efficient force diagram of the excavator has been validated, and a technical solution in the form of the operational equipment with the closure of the workload has been developed.

Using the operational equipment with the closure of the workload will reduce significantly the energy consumption level and improve the energy efficiency of single-bucket excavators.

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