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Increasing power efficiency of open-pit excavators

O A Lukashuk[1], A P Komissarov[1,2] and K Y Letnev[1,*]

[1] Department of Machine Building, Institute of New Materials and Technologies, Ural Federal University, 19 Mira Street, Yekaterinburg, 620002, Russia
[2] Mining Engineering Faculty, Ural State Mining University, 19 Mira Street, Yekaterinburg, 620002, Russia

* ptmir@inbox.ru

Abstract. It is shown that a working process of rock excavation realized by an open-pit front-shovel excavator is characterized by an increased power intensity due to counteraction of its main actuating mechanisms (lifting and thrusting), whose operational parameters have to be properly matched during their joint action to provide more efficient excavation. A computational experiment allowed to determine an actual work of lifting and thrusting forces immediately involved in developing an excavated face. It was further established that power inputs depend on the bucket position relative to the working area of an excavator, and such regions of that area where those inputs are higher were determined. Differentiated calculation of the inputs was carried out, based on the type of a conducted operation – power inputs originating from excavating, from counteraction of the main mechanisms, and from lifting operational equipment parts and rock. The power intensity of excavation was estimated for various regions of the workspace of the excavator. The proposed method for calculating the power inputs of rock excavation using the operational equipment of an open-pit excavator would allow to determine an energy characteristic of the excavator for specific mining and technical conditions of operation.

1. Introduction

Designs of electromechanical crawler-mounted open-pit excavators (mechanical shovels) are technically quite unique but often show many signs of discrepancy between their technical level and low quality of the control system which is in charge of the working process of rock excavation.

It is quite difficult to realize the full technical potential of an excavator and achieve designed engineering-and-economic performance in actual operational conditions due to the complexity of matching and coordinating working motions (lifting and thrusting) of its main actuating mechanisms while moving the bucket about the excavation face.

Technical sources related to open-pit excavators [1–14] are insufficient both in covering the topic connected to analyzing the operation of the main mechanisms in specific mining and technical conditions while developing an excavation face and in determining power-force characteristics of the process of excavation which utilizes a front-shovel operational equipment.

Evaluating actual power inputs would allow to form energy-efficient schemes of excavation in specific operational conditions.

2. The goal of the research and its tasks

The research is aimed at increasing the power efficiency of open-pit excavators (mechanical shovels) by properly matching operational parameters of their main mechanisms, which act in joint during the process of rock excavation.

The goal is achieved by realizing the following tasks:

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- determining actual power inputs of rock excavation in specific working conditions;
- assessing how technological parameters (stope width, broken-rock excavation face height, etc.) impact power inputs.

The object of the research is the process of rock excavation using a front-shovel operational equipment of open-pit excavators.

The subject of the research is the analysis of the impact which technological parameters have on the power intensity of the rock excavation process.

The methods of the research are a simulation modeling and computational experiment.

3. The process of rock excavation

The process of rock excavation using a front-shovel operational equipment of open-pit excavators is characterized by a substantially-increased power intensity of the process due to higher power inputs needed to lift both operational equipment parts and the rock extracted up to the face height (development of broken rock).

The power inputs of rock excavation are determined by the total work of lifting and thrusting forces while the corresponding main actuating mechanisms are joined to perform the task.

A current work of a force (lifting or thrusting) is expressed as

$$A_i = 0.5(P_i + P_{i+1})\Delta t \,, \tag{1}$$

where P_i and P_{i+1} are current powers of force calculated for ***i***-th and i+1 points of the bucket motion path (top of its cutting edge); Δt is a duration of the bucket motion in the interval of (i, i+1).

On the basis of a developed simulation model of excavation, a computational experiment was carried out to calculate power inputs of rock excavation for an EKG-20A excavator.

Initial values of the parameters realized at the cutting edge of the bucket are as follows:

- excavation velocity – V_E = 1 m/s;
- excavation-resistance force (its tangent) for a calculated excavation height of H_E = $H_{E.calc}$ = 12 *m* – $F_E^\tau = 325$ kN and for H_E = $H_{E.max}$ = 18 m – $F_E^\tau = 217$ kN.

Tables 1 and 2 show powers and works of lifting and thrusting forces along with power inputs of rock excavation when the bucket moves along equidistant paths [13] – initial, intermediate and terminate, that is at the boundaries and in the center of the working area of the excavator.

As it follows from the data cited, power inputs vary a lot depending on the bucket position in the workspace.

Thus, as the bucket moves along its initial path, the power inputs of rock excavation rise due to increased works of the thrusting (at the beginning of excavation) and lifting forces (in the upper section of the excavation face), reaching their maximum of A_Σ = 2.07 MJ (at the beginning) and A_Σ = 2.56 MJ (in the upper part).

When the bucket moves along the intermediate path, the total power inputs change just a little, with the exception of excavation in the upper section of the face. There, the lifting velocity falls abruptly as the inclination angle of the lifting rope decreases, and so does the power of the lifting force, as well. Meanwhile, the engine of the thrusting mechanism becomes a driving one (thrusting and excavating velocities practically match), and the calculated power of the thrusting force abruptly rise. In that case, the power inputs reach their maximum of A_Σ = 2.66 MJ.

When the bucket moves along the terminate path, the total power inputs change insignificantly.

In general, the total inputs depend both on the power needed to overcome the excavation resistance force (A_{exc}) and lift the operational equipment parts and rock (A_{lift}) and on the power inputs (A_{MM}) originated from «counteraction» of the main mechanisms (different directions of lifting and thrusting velocity vectors).

Table 3 cites values of separate and total power inputs.

The cited data shows that with a rise of excavation height there comes a substantial increase of the power inputs caused by counteraction of the main mechanisms – lifting velocity being directed towards the head block of the boom and thrusting velocity – towards the face.

Table 1. Results of the computational experiment ($H_E = H_{E.calc}$).

№	Coordinates of point *K* (m)		Lifting and thrusting velocities (m/s)		Lifting and thrusting forces (kN)		Powers of forces (kW)		Works of forces (MJ)		Total power inputs (MJ)
	X_K	Y_K	V_L	V_T	F_L	F_T	P_L	P_T	A_L	A_T	A_Σ
Initial path (X_{K0} = 10 m)											
1	10.00	0	0.94	-0.82	528	-495	494	408			
2	11.15	2	0.89	-0.74	589	-500	526	372	1.17	0.90	2.07
3	12.30	4	0.81	-0.61	642	-516	522	316	1.21	0.79	2.00
4	13.45	6	0.69	-0.40	759	-501	522	201	1.20	0.60	1.80
5	14.60	8	0.57	-0.10	936	-495	536	49	1.22	0.29	1.51
6	15.75	10	0.58	0.23	1152	-520	671	121	1.39	0.20	1.59
7	16.90	12	0.69	0.50	1349	-547	934	275	1.85	0.46	2.31
Intermediate path (X_{K0} = 14 m)								Σ	8.04	3.21	11.28
8	14.00	0	0.87	-0.61	801	-195	696	119			
9	15.15	2	0.82	-0.48	838	-196	685	94	1.59	0.25	1.84
10	16.30	4	0.76	-0.30	876	-183	662	56	1.55	0.17	1.72
11	17.45	6	0.70	-0.10	921	-142	642	13	1.50	0.08	1.58
12	18.60	8	0.66	0.13	978	-59	645	8	1.48	0.03	1.51
13	19.75	10	0.64	0.33	1040	78	661	26	1.50	0.04	1.54
14	20.90	12	0.59	0.50	1093	296	640	148	1.50	0.20	1.70
Terminate path (X_{K0} = 18 m)								Σ	9.12	0.77	9.89
15	18.00	0	0.79	-0.39	1017	111	799	44			
16	19.15	2	0.73	-0.25	1055	148	774	38	1.81	0.10	1.91
17	20.30	4	0.68	-0.09	1097	214	742	20	1.74	0.07	1.81
18	21.45	6	0.61	0.07	1147	320	702	24	1.66	0.05	1.71
19	22.60	8	0.53	0.23	1210	480	644	113	1.55	0.16	1.71
20	23.75	10	0.42	0.38	1292	709	546	269	1.37	0.44	1.81
21	24.90	12	0.27	0.50	1416	1030	377	515	1.06	0.90	1.96
								Σ	9.19	1.72	10.91

Table 2. Results of the computational experiment ($H_E = H_{E.max}$).

№	Coordinates of point *K* (m)		Lifting and thrusting velocities (m/s)		Lifting and thrusting forces (kN)		Powers of forces (kW)		Works of forces (MJ)		Total power inputs (MJ)
	X_K	Y_K	V_L	V_T	F_L	F_T	P_L	P_T	A_L	A_T	A_Σ
Initial path (X_{K0} = 10 m)											
1	10.00	0	0.94	-0.82	375	-554	351	456			
2	11.15	2	0.89	-0.74	436	-538	389	400	0.85	0.99	1.84
3	12.30	4	0.81	-0.61	481	-538	391	330	0.90	0.84	1.74
4	13.45	6	0.69	-0.40	580	-505	399	202	0.91	0.61	1.52
5	14.60	8	0.57	-0.10	727	-471	417	46	0.94	0.29	1.23
6	15.75	10	0.58	0.23	911	-461	530	108	1.09	0.18	1.27
7	16.90	12	0.69	0.50	1078	-461	747	232	1.47	0.39	1.86
8	18.05	14	0.80	0.68	1172	-414	933	280	1.93	0.59	2.52
9	19.20	16	0.84	0.78	1123	-206	942	161	2.16	0.40	2.56
10	20.35	18	0.58	0.85	866	467	501	396	1.66	0.64	2.30
Intermediate path (X_{K0} = 14 m)								Σ	11.91	4.93	16.84
11	14.00	0	0.87	-0.61	636	-275	552	167			
12	15.15	2	0.82	-0.48	670	-261	547	125	1.27	0.34	1.61
13	16.30	4	0.76	-0.30	702	-236	531	72	1.24	0.23	1.47
14	17.45	6	0.70	-0.10	739	-186	516	18	1.21	0.11	1.32
15	18.60	8	0.66	0.13	787	-101	519	13	1.19	0.04	1.23
16	19.75	10	0.64	0.33	842	27	535	9	1.21	0.03	1.24
17	20.90	12	0.59	0.50	890	217	521	109	1.22	0.14	1.36
18	22.05	14	0.44	0.63	939	506	414	317	1.08	0.49	1.57
19	23.20	16	0.15	0.72	1055	935	156	670	0.66	1.14	1.80
20	24.35	18	-0.21	0.78	1353	1530	288	1196	0.51	2.15	2.66
								Σ	9.59	4.67	14.26

Table 3. Distribution of power inputs of rock excavation.

Path	A_Σ	A_{exc}		A_{lift}[a]		A_{MM}	
	MJ	MJ	%	MJ	%	MJ	%
Excavation height H_E = 12 m							
Initial	11.28	4.50	39.9	4.95	43.9	1.83	16.2
Intermediate	9.89	4.50	45.5	4.95	50.1	0.44	4.5
Terminate	10.91	4.50	41.2	4.95	45.4	1.46	13.4
Excavation height H_E = 18 m							
Initial	16.84	4.50	26.7	8.25	49.0	4.09	24.3
Intermediate	14.26	4.50	31.6	8.25	57.9	1.51	10.5

[a] Power inputs to lift the excavator stick are left out since coordinates of the center of stick masses change insignificantly

Thus, rock excavation by means of a front-shovel open-pit excavator involves significant changes in power inputs depending on the region within its working area, which could be explained, mainly, by how the mechanism of operational equipment (which connects the main mechanisms with the bucket) influences conversion of the mechanical energy parameters of the engines of the main mechanisms into the power-force parameters realized at the cutting edge of the bucket.

4. Conclusion

Finding an energy characteristic of an open-pit excavator on the basis of a computational experiment allows to determine how power inputs form and impact the rock excavation within the working area of the excavator. The results of calculations using variable inputs could be used to synthesize rational designs of the operational equipment of the excavator.

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