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OPTIMAL CONTROL SYSTEM OF DIESEL AUTOMOTIVE ENGINEERING BY EXAMPLE OF OPEN PIT MOTOR TRANSPORT

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Abstract. *The paper investigates the optimal control system of diesel automotive engineering with application of complex criteria, depending on fuel consumption rate and travel time, with adjustable coefficients of physical process mathematical model, considering influence of disturbing effects factors. This control principle allows saving fuel consumption rate, reducing transport influence on environment, and also reducing the importance of human factor for motor transport control.*

Keywords: optimal control, fuel consumption, quarry road transport, pit road transport, mobile resource management, vehicle control

SYSTEM AUTOMATYCZNEGO ZARZĄDZANIA ZESPOŁEM SAMOCHODÓW Z SILNIKAMI DIESLA NA PRZYKŁADZIE TRANSPORTU SAMOCHODOWEGO W KAMIENIOŁOMACH

Streszczenie. *W artykule zostało rozpatrzone optymalne sterowanie procesem przemieszczania pojazdów z zastosowaniem złożonego kryterium, zależnego od zużycia paliwa i czasu przejazdu, ze zmiennymi współczynnikami modelu matematycznego fizycznego procesu, uwzględniając wpływ czynników zakłócających. Otrzymany system sterowania pozwala na oszczędne zużycie paliwa, zmniejszenie wpływu transportu na środowisko i obniżenie wpływ czynnika ludzkiego na zarządzanie transportem samochodowym.*

Słowa kluczowe: sterowanie optymalne, zużycie paliwa, transport samochodowy w kamieniołomach, zarządzanie transportem samochodowym, ocena stanu technicznego

Introduction

Transport Strategy of Republic of Kazakhstan (hereinafter – the Strategy) approved in Kazakhstan up to 2015 [1] has a federal value and was stated in "Kazakhstan at the threshold of the new breakthrough in its development", the Message of the President of the Republic of Kazakhstan to the People of Kazakhstan dated March 1, 2006. The Strategy was developed by the Ministry of Transport and Communication of the Republic of Kazakhstan. The target of the Strategy is "Faster growth of transport and communication complex able to fully satisfy requirements of economy and population in transportation services". The basic strategic missions and principles are as follows:

- achievement of highest efficiency of transportation processes and reduction of transport component share in finished goods price for internal, transit, and export-import communication;
- competitive recovery of Kazakhstan transportation system at the cost of innovative technologies and clustered development of infrastructure;
- providing safety for transportation processes, reducing the number and severity of transport accidents; providing ecological safety and rational utilization of energy resources.

1. Background literature overview

An automobile is one of the most popular means of transport in the structure of the transportation cycle used at development of deposits [9, 11]. Development of mining operations and increasing of open pit depths leads to increasing of mine rock transportation amount, which at the same time causes the deterioration of road conditions and affects the cost-performance indicators of rock mass transportation [1]. Besides that, the ecological situation due to exploitation of diesel trucks accompanied by emissions of toxic substances into the atmosphere also takes a turn for the worse [13].

Analysis of data processing results [6] with regard to reliability of open pit motor transport at the enterprises of mining industry shows that about 32% of all failures are accounted for the engine and its systems. The main causes are both increasing of automobile run and corresponding deteriorated technical conditions (ageing, wearing of friction parts, etc.), and also deficiencies in operation of maintenance team supporting its working efficiency.

Besides different emergencies often occur during mining operations [14], they could be conditionally split into four basic groups: poor technical mine and road conditions, violation of traffic rules, inefficient organization of motor transport performance, technical failures of dump trucks. In addition, as statistics analysis shows [14], about 20% of drivers causing accidents, were the 1st category drivers, more than one third were the 2nd category drivers, and almost 50% were the 3rd category drivers. This clearly points to the need to improve skills of drivers. A lot of accidents also occur at the night shift, which is related to higher stress of drivers and influences their working efficiency due to over-fatigue. After increasing the capacity and sizes of open pit motor transport, and also complication of transport communication the matter of accident free traffic became one of top priorities.

Besides, it is also required to provide not only safe traffic of the motor transport, but also its optimal operating mode with regard to fuel consumption and travelling speed [5, 14]. Optimal control of motor transport traffic should be provided by the driver, but it is not always possible due to human factors, such as qualifications, fatigue, inattention etc.

2. Goal and problem setting

The aim of this research is based on the performed analysis, the aims and objectives of the Strategy. The research is targeted at improvement of open pit motor transport working efficiency in the process of its exploitation. The overall goal of work is the reduction of human factor influence on trucks driving in the process of their exploitation in the mining sphere. The set goal can be achieved by solution of the following problem: development of mathematical model and optimal control system for diesel automotive engineering in the process of exploitation.

3. The procedure

Developed system realizes optimal control with an application of improved physical process model. It consists of three levels: I – upper, II – middle, and III – lower (Figure 1). The upper level keeps truck parameters and traffic route information. The middle level performs search of optimal crank shaft rotations (CS), fuel injection advance angle (FIAA) and gear in accordance with preset efficiency criteria. The lower level performs automated control of fuel rack supporting minimum rotations at each section of a traffic route.

Let us examine the control system structure in details.

Upper Level I consists of the following structural blocks:

- Block 1 has the following preset parameters for each type of truck: minimum rotation speed of CS $n_{e\ min}$ and maximum rotation speed of CS $n_{e\ max}$; weight of truck G_a; transmission efficiency factor η_{tr}; k – air resistance coefficient; F – truck front surface; r_k – driving wheel radius; i_k – drive ratio of gearbox (GB) etc.;
- Block 11keeps the mathematical model of truck and engine;
- Block 12 performs specification of model parameters based on measuring results;
- Block 13 implements the target function of optimal control;
- Block 14 keeps the route memory, including minimum $\vartheta_{a\ min}$ and maximum $\vartheta_{a\ max}$ travel speed at different sections of traffic routes. The speed limit is set in accordance with traffic safety according to the traffic rules and road conditions. Besides there is a road resistance coefficient ψ for each section of route in this block. A skilled driver (expert) can correct travel speed without exceeding the preset range. In such case corrections in the block 14 are required.

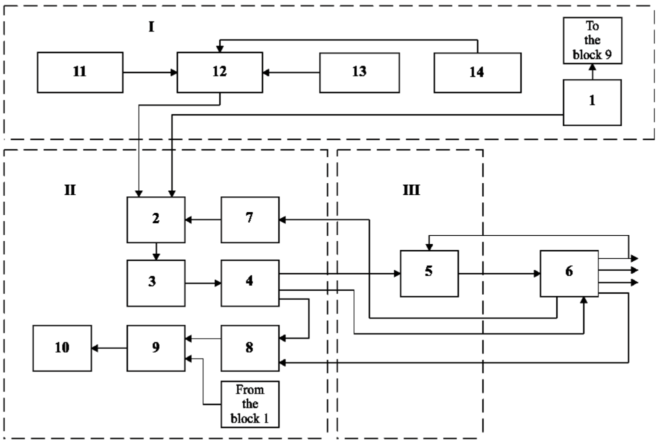

Fig. 1. Block scheme of an optimal control system

Middle Level II consists of the following structural blocks:

- in Block 2 adjustment of optimal control equations coefficients is performed;
- Block 3 is designed for numerical solution of optimal control equations;
- in Block 4 the calculated optimal variables are transferred;
- in Block 7 adjusted model coefficients are recorded;
- in Block 8 calculation of deviations of optimal values from current measured value is performed;
- in Block 9 comparison of calculated deviation in the block 8 with preset maximum deviation along with the calculation of percentage is performed, which is the validation of fuel equipment (FE) technical conditions;
- in Block 10 conclusions on the validation of FE technical conditions as per one parameter are made.

Lower Level III consists of structural Block 5 – control block regulating magnitudes of variables at the outlet of a control object (Block 6) calculated in Block 4.

To perform computer modeling a control object's mathematical model is used as a control object (block 6). After the system is introduced in site, its mathematical model is replaced by a real truck.

A mathematical model of a control object represents both a model of a diesel combustion engine (CE) and a truck model as a whole.

The mathematical model of a diesel engine in the form of a control object regarding rotation speed of CS n_e from rack sghift h and load N (and also from resistant moment coefficients K_{d2} and drive torque K_{d1}) is given in the following equation [5, 7]:

$$n_e = \frac{K_{d1}\cdot h - K_{d2}\cdot N}{T_d\cdot p+1} \tag{1}$$

Dependence of the truck travel speed from CS rotation speed and drive ratio of GB [2]:

$$\vartheta_a = 0,377\cdot\frac{r_k\cdot n_e}{i_k\cdot i_0} \tag{2}$$

where r_k – driving wheel radius; n_e – CS rotation speed; i_k – drive ratio of GB; i_o – drive ratio of main gear; 0,377 – speed conversion factor in km/h.

The mathematical model of truck fuel consumption could be determined basing on the following equation [4]:

$$Q_p = \frac{g_e\cdot(G_a\cdot\psi+0,077\cdot k\cdot F\cdot\vartheta_a^2)}{0,36\cdot10^5\cdot\eta_{TP}\cdot\rho_T} \tag{3}$$

where g_e – specific fuel consumption; G_a – estimated truck weight; ψ – road resistance coefficient; k – air resistance coefficient; F – truck front surface; ϑ_a – truck speed; η_{mp} – transmission performance coefficient; ρ_T – fuel density;

Equation (3) is approximate, because the following variables were not considered: rack moving, drive ratio of GB and main gear, wheel radius and engine load. To eliminate these violations, using (1) and (2) on the basis of (3), and as a result of corresponding re-expressions we obtain an improved mathematical model of fuel consumption rate considering above mentioned variables:

$$Q_p = \frac{g_e\cdot\left(G_a\cdot\psi\cdot i_k^2\cdot i_0^2+0,011\cdot k\cdot F\cdot r_k^2\cdot\left(\frac{K_{d1}\cdot h-K_{d2}\cdot N}{T_d\cdot p+1}\right)^2\right)}{0,36\cdot10^5\cdot\eta_{TP}\cdot\rho\cdot i_k^2\cdot i_0^2} \tag{4}$$

where Q_p – fuel consumption; r_k – driving wheel radius; i_k – drive ratio of GB; i_o – drive ratio of main gear; N – engine load; h – rack moving; g_e – specific fuel consumption; G_a – truck designed weight; ψ – road resistance coefficient; k – air resistance coefficient; F – truck front surface; η_{TP} – transmission performance coefficient; ρ – fuel density.

Based on (1, 2, 4) the simulation modeling of dependences of fuel consumption (Q_p), CS rotation speed (n_e), and truck travel speed (ϑ_a) on the time in the case of fixed fuel rack and gear were performed. The results are given in Figure 2.

Development of an optimal control system.

The optimal control system includes a mathematical model of a control object physical process, the selection of a target function and limitation for control and controlled variables.

We develop a mathematical model of a diesel engine and truck fuel consumption in the process of their exploitation.

The fuel consumption could be determined by the following formula [10]:

$$Q_p = \frac{g_e\cdot N_e}{10000\cdot\vartheta_a\cdot\rho} \tag{5}$$

where g_e – specific fuel consumption kg/(h.p.·h); N_e – applied engine effective power; ϑ_a – travel speed; ρ – fuel density.

Engine brake power is determined by the formula [4]:

$$N_e = G_a\cdot\psi\cdot\vartheta_a+0,077\cdot k\cdot F\cdot\vartheta_a^3 \tag{6}$$

where: G_a – truck weight;
ψ – total road resistance [3];
k·F – truck wind shape factor [4].

Considering transmission performance coefficient the formula (6) will take the following form:

$$N_e = \frac{G_a\cdot\psi\cdot V_a+0,077\cdot k\cdot F\cdot\vartheta_a^3}{\eta_{TP}} \tag{7}$$

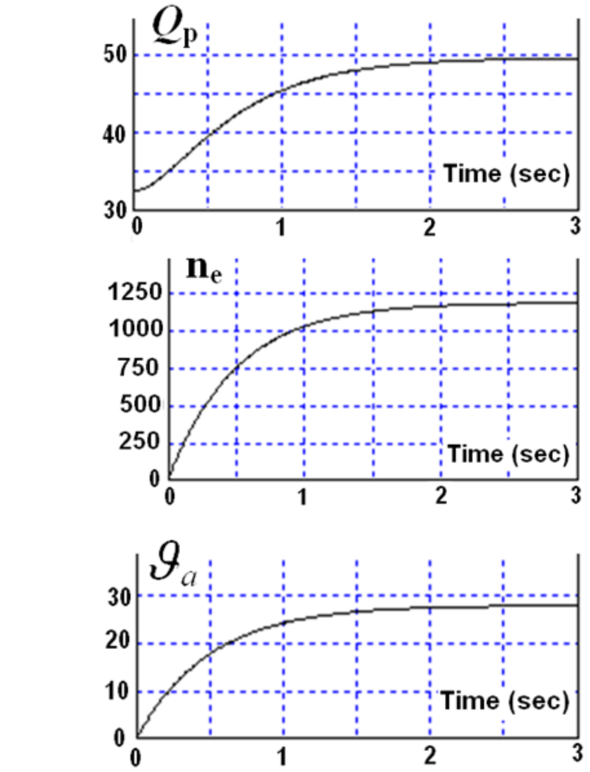

Fig. 2. Modeling results

If an engine is operating in conditions of variation of FIAA values and CS rotation speed, the fuel specific consumption changes, which can be seen on the full-load curve [3, 4, 5, 10, 12]. The dependence of fuel specific consumption is usually represented either for different CS rotation speed, or for different FIAA and definite CS rotation speed. Approximating the values by complete quadric polynomial with the help of Curve Expert Pro software, we can make a diagram (Figure 3) of the interpolation dependence of fuel specific consumption on CS rotation speed and FIAA. It allows calculating specific consumption against any of their values:

$$g_e = a + b \cdot n_e + c \cdot \varphi + d \cdot n_e^2 + e \cdot \varphi^2 + f \cdot n_e \cdot \varphi \tag{8}$$

where *a, b, c, d, e, f* are coefficients whose values depend on the engine type; φ – FIAA; n_e – CS rotation speed.

Based on dependence of truck fuel consumption (5), effective power (7), truck travel speed (2), and also dependence of fuel specific consumption (8) we obtained the mathematical model of fuel consumption:

$$Q_p = \frac{G_a \cdot \psi}{10000 \cdot \eta_{mp} \cdot \rho}(a + b \cdot n_e + c \cdot \varphi + d \cdot n_e^2 + e \cdot \varphi^2 + f \cdot n_e \cdot \varphi) + \frac{0{,}077 \cdot k \cdot F \cdot r_k^2}{10000\eta_{mp} \cdot \rho \cdot (i_k \cdot i_0)^2}(a + b \cdot n_e + c \cdot \varphi + d \cdot n_e^2 + e \cdot \varphi^2 + f \cdot n_e \cdot \varphi)n_e^2 \tag{9}$$

Dependence (9) represents the dependence of fuel consumption on FIAA and CS rotation speed, drive ratio of GB, truck weight, road conditions, and other parameters.

The next stage of optimal control system development lies in selection of the target function (optimality criterion). Optimization is performed based on the minimum fuel consumption and minimum time of transportation. At that these parameters are mutually exclusive, i.e. minimum transportation time is achieved at minimum fuel consumption and vice versa. Based on uniqueness principle [8], the optimality criterion will be a linear combination of two targeted functions:

1. minimum fuel consumption criterion $Q_p=f(n_e,\varphi)=min$;
2. minimum travelling time criterion $t=f(\vartheta_a)=min$.

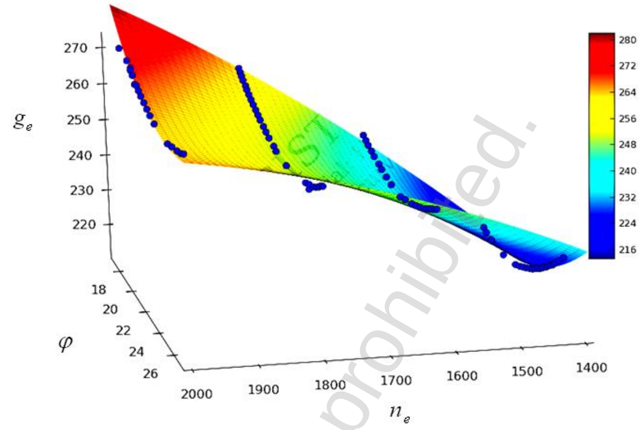

Fig. 3. Dependence of fuel specific consumption on FIAA and CS rotation speed

After combining of these criteria the following criterion could be obtained:

$$Cf = p_1 \cdot Q_p + p_2 \cdot t \tag{10}$$

Where p_1 and p_2 – weight of optimal criteria importance. We assume $p_1+p_2=1$.

The minimum travelling time is achieved by the increase of travelling speed.

So, optimal control could be represented as an optimization problem:

$$Cf = p_1 \cdot Q_p + (1 - p_1) \cdot \frac{1}{\vartheta_a} = \min \tag{11}$$

when the following conditions are satisfied:

1. Mathematical model of fuel consumption is represented by dependence (9);
2. Mathematical model of truck travelling speed is given by dependence (2); and following limitations:
   - $n_{e\min} < n_e < n_{e\max}$,
   - $\varphi_{\min} < \varphi < \varphi_{\max}$.

In the process of solving the assigned task we will obtain the optimal values of FIAA and CS rotation speed at a definite gear. In the picture 4 the example of dependence of targeted function on CS rotation speed at FIAA fixed value φ, and weight of importance p_1 for different gears i_k is given.

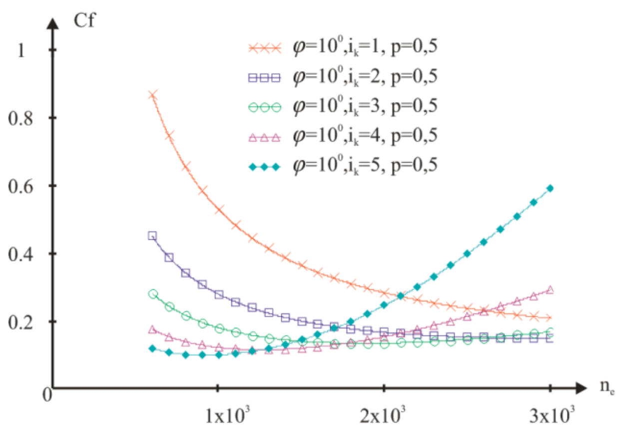

Fig. 4. Dependence of targeted function on FIAA values, CS rotation speed, and definite gear

As we see from the picture 1, optimal control system allows evaluating of diesel engine fuel equipment technical condition (blocks 8, 9, 10). In the process of motor transport exploitation the wearing of fuel equipment spare parts occurs, causing deviation of parameters from normal values. By way of evaluating of these deviations, the wear rate of fuel equipment could be determined. FIAA was selected for such an evaluation.

Evaluation of fuel equipment condition is performed based on the following formula:

$$Z = \frac{\left|\varphi_{opt} - \varphi_{izm}\right|}{\Delta\varphi_{\max}} \cdot 100\% \qquad (12)$$

where Z – evaluation of fuel equipment technical condition,
φ_{opt} – optimal value of FIAA,
φ_{izm} – measured values of FIAA,
$\Delta\varphi_{max}$ – maximum allowed deviation of FIAA from the nominal value.

4. Conclusions

So developed optimal control system allows automating of motor transport control process in accordance with optimality criterion, thus allowing not only reducing of human factor influence for the process of motor transport driving, but also reducing of fuel consumption, not only reducing the negative influence of motor transport for environment, but also performing approximate evaluation of fuel equipment technical condition of truck diesel engine.

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