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EXTERNAL EXCITATIONS AND DISTURBANCES WITH BUCKET WHEEL EXCAVATORS AS NON-LINEAR AND RANDOM FUNCTIONS

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Abstract. *On the example of the driving system of the boogie wheel on the concrete bucket wheel excavator, the paper analyses external effects which stem from the electric motors and resistance to motion of the spoons. The curves of moments of starting three-phase asynchronous cage and slide-disc electric motors are considered and analytically modeled as non-linear functions of the angular velocity* $M = f(\varphi)$. *Since the resistance of digging is not uniform, due to the alternating smaller number of spoons engaged with the non-homogeneous mass of ground, and different pressure angles, it is modeled as a random function of time. Graphical interpretation is also provided for the given disturbances. The knowledge of the more real changes of these disturbances enables a more adequate design of the bucket wheel excavator which will be of more use in exploitation.*

1. INTRODUCTION

Bucket whell excavators represent complex machines of mining technology within modern technology for surface exploitation of coal. They consist of a complex spatial structure, several driving systems, and a steering device. Among all the mechanisms, the drive of the bogie-wheel with spoons, located at the top of the arrow, is the most characteristic one. The bucket wheel excavator's actual process of digging is realized by combining continuous rotation of the boogie-wheel in the vertical plane with the arrow's movement in the horizontal plane. As a result of the drive's performances, characteristics of the soil, and inequality of digging resistances on the spoons, the bucket wheel excavator is subject to a number of external loads with a dynamic random character of change. As a consequence, the vital parts of the excavator's structure and of its driving systems are exposed to changeable load, which, when it exceeds critical values, causes damage and delay in the work of the entire system.

An adequate design and a correct analysis of the work of the bucket wheel excavator both require knowledge of the character of change of all external excitations and distur-

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bances during their exploitation. They can be obtained experimentally or analitically. In variant design of the bucket wheel excavator, the analitical procedure is favoured, because of a simpler and cheaper solution to this problem. The paper therefore aims at a more realistic analytic modelling of external excitations which stem from electric motors (in further text: motors) and from disturbances caused by resistance to digging. The goal is to analyze the work of such systems by applying the simulation method.

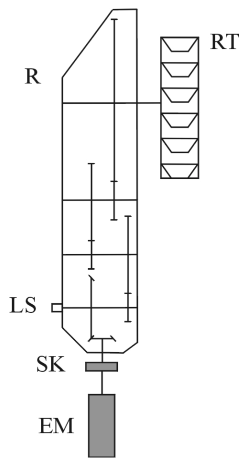
2. Driving System of the Excavator's Boogie-Wheel

During exploitation, the carrying structure and the driving mechanisms of the bucket wheel excavator, i.e. their component parts, are exposed to changeable load *Q = f(t)* (moments, forces), which are mainly of stochastic nature. This especially applies to the work of the boogie-wheel when digging non-homogenous massifs (coal, country rock, rock etc.), with a highly dynamic load which is a consequence of periodic contact of the spoons with the soil.

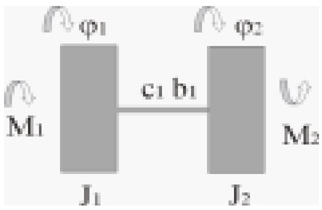
Workloads as functions of time *Q(t)* are obtained experimentally or analitically. In the first case, tensometric measurements on already derived identical or similar bucket wheel excavators in adequate working conditions are used. This procedure is highly reliable, though costly, so that in the phase of their design analytic methods are frequently used. They are based on modelling bucket wheel excavators and the simulation of their work.

Fig.1.a shows the driving mechanism of the boogie-wheel of the excavator SRs 470.20.3 LAUHAMER, as a real system consisting of a motor (EM), an elastic coupling with a brake (SK), a four-step reducor (R) with a lamellar coupling (LS) on the reducor's second shaft, and a boogie-wheel (RT) with 8 spoons. Figure 1.b represents its equivalent elastic-kinetic model with two revolving masses and one elastic constraint [1].

a)



b)



$$J_1 \cdot \ddot{\varphi}_1 + b_1 \cdot (\dot{\varphi}_1 - \dot{\varphi}_2) + c_1 \cdot (\varphi_1 - \varphi_2) = M_1 = M_M(\dot{\varphi})$$
$$J_2 \cdot \ddot{\varphi}_2 - b_1 \cdot (\dot{\varphi}_1 - \dot{\varphi}_2) - c_1 \cdot (\varphi_1 - \varphi_2) = M_2 = -F_T(\psi) \cdot R$$

$$M_t = c_1 \cdot \Delta\varphi = c_1 \cdot (\varphi_1 - \varphi_2)$$

Fig. 1. a) Scheme of the driving system of the boogie-wheel of bucket wheel excavator SRs 470.20.3 LAUHAMER
b) Reduced elastic-kinetic model with two revolving masses and its mathematical model

The characteristics of the real system's components (Fig. 1.a) are: motor with power $P_M = 250$ kW, number of revolutions $n_1 = 960$ min^{-1}, and nominal moment $M_n = 2487$ Nm, the reducor's gear ratio is $i_R = 128$, the boogie-wheel has 8 spoon arranged along diameter $D_{RT} = 6.7$ m, number of revolutions $n_{RT} = 7.5$ min^{-1}. Characteristics of the equivalent model when reducing through the reducer's input shaft (Fig. 1.b) are: moments of inertia, driving $J_1 = 17.2$ kgm^2, i.e. followed mass $J_2 = 6.25$ kgm^2, rigidity $c_1 = 86210$ Nm and damping $b_1 = 14.00$ Nms of the elastic constraint.

3. Modeling of external loads of bucket wheel excavators

Apart from other reasons, dynamic behaviour of mechanisms primarily depends upon external disturbances and excitations. These are primarily excitations of the motor and the brake, as well as disturbances caused by various types of resistance to digging. Most frequently these are aperiodic functions of time, which are a consequence of the characteristics of the mechanism's parts. In dynamic modelling, certain simplifications are commonly used, depending on the type of the equivalent model. Since the paper will mainly deal with the torsional model, the disturbances are given in the form of the torsion moment as the function of time $M = f(t)$ or number of revolutions (angular velocity) $M = f(n) = f(\dot{\varphi} = \pi \cdot n/30)$.

3.1 Modelling of the curve of starting the motor

Asynchronous motors are built into the boogie-wheel's driving system: slide-ring and cage motors with a short-circuited rotor. Cage motors, which have a number of advantages over slide-ring motors, are used more frequently nowadays. What is characteristic of them is their compact, easy, and cheap structure. They are highly reliable in work, and are manufactured with a cylindrical or a conoid rotor [2].

Depending on conditions of work, it is possible to start cage motors in different ways. They are usually started directly, although this can also be done indirectly, by means of: the star-triangle switch (in a single or in several steps), stator resistors, a special coiling. Since the motor for the drive of the boogie-wheel is started when the boogie-wheel is not in the NC sequence (it moves the revolving masses only), the moment is of no special interest. This paper will present only the basic premises for the analysis of the process of starting the motor.

The manufacturer usually gives the characteristic of starting the motor $M = f(n) = f(\dot{\varphi} = \pi \cdot n / 30)$; most frequently, it is a curve of a higher order which cannot be described by the corresponding explicit function. In this paper, this curve was modelled in such a way as to view two if its intervals separately (Fig. 2): from the starting moment (M_p) to the maximal moment (M_m) and from the maximal moment (M_m) to the nominal moment (M_n). The first interval can be defined by a polynome of the fourth order [3]:

$$M(\dot{\varphi}) = A_4 \cdot \dot{\varphi}^4 + A_3 \cdot \dot{\varphi}^3 + A_2 \cdot \dot{\varphi}^2 + A_1 \cdot \dot{\varphi} + A_0 \tag{1}$$

since three points through which the curve must pass are known (M_p), (M_s) and (M_m), and also two points where the curve has horizontal tangent lines (M_s) and (M_m).

The second interval is best desrcribed by the so-called Clos's equation:

$$M(s) = \frac{2 \cdot s \cdot s_m \cdot M_m}{s^2 + s_m^2} \tag{2}$$

where: $s = 1 - \dot{\varphi} / \dot{\varphi}_0$ - the so-called sliding at any point of the interval,

$s_m = 1 - \dot{\varphi}_m / \dot{\varphi}_0$ - sliding at the point of maximal moment,

$\dot{\varphi}_m$ - angular velocity at maximal moment,

$\dot{\varphi}_0$ - synchronous angular velocity.

Figure 2 represents the modelled curve of starting a concrete motor.

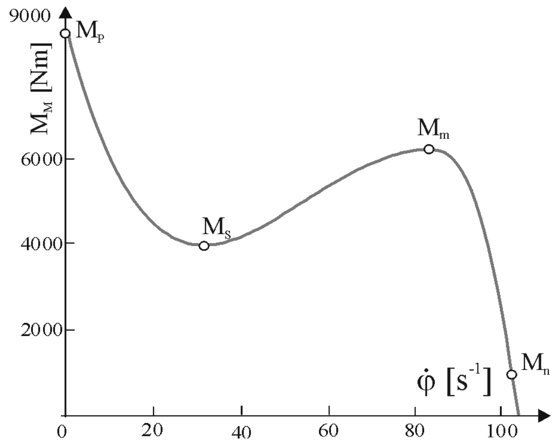


Fig. 2. Curve of starting the motor

3.2 Modelling of resistance to digging

The process of digging ore (country rock) by means of the bucket wheel excavator is continual, since at each moment of work at least one spoon seprates parts of the massif (cutting), twists the separated part, crushes it and takes it with a spoon (fills a spoon). Digging is performed by simultaneously rotating the rotor around its axis and by rotating the rotor's arrow with the rotor in the horizontal plane.

Resistance to digging has a relatively unknown direction in space, with point of application on the cutting edge of the tooth, or on the spoon's blade. At any rate, it can be separated into three mutually normal componments.

$$\vec{F}_K = \vec{F}_T + \vec{F}_N + \vec{F}_B \tag{3}$$

where:

$\vec{F}_T$ - tangent (to the trajectory of the cutting edge in the rotor's plane) component of resistance,

$\vec{F}_N$ - normal (to the trajectory and $\vec{F}_T$ in the rotor's plane) component of resistance,

$\vec{F}_B$ - side (normal to the rotor's plane, i.e. components $\vec{F}_T$ and $\vec{F}_N$) component of resistance.

Components $\vec{F}_N$ and $\vec{F}_B$ are determined with regard to $\vec{F}_T$ by means of relations: $\vec{F}_N = k_N \cdot \vec{F}_T$ and $\vec{F}_B = k_B \cdot \vec{F}_T$, where: k_N and k_B are coefficients of proportionality of the normal and side components of resistance to digging [3].

More or less precisely, each of the resistances to digging can be determined by applying adequate methods. In practice, however, it is more frequently required to determine total resistances, since they are necessary for correct selection and dimensioning of the bucket wheel excavator's parts. In this paper, special attention will be paid to the tangent component of resistance (Fig. 3).

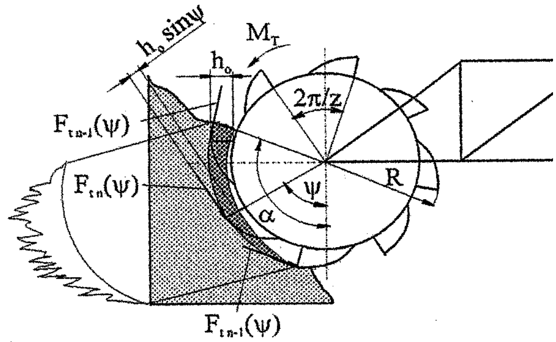


Fig. 3. Change of the tangent force in the process of digging

The resistance of cutting on the excavator's rotor (the tangent component) is the basic component of resistance to digging. It can be represented as the result of specific linear resistance to digging k_l (characteristic of the soil) multiplied with the mean sum of the length of the cutting edges of blades l_{sr}. However, since specific resistance to digging k_l is a random value which changes depending on changes in the digging environment, resistance to digging cannot be represented by a single mathematical function.

A relatively high degree of accuracy regarding the change of the tangent force on the spoons (Fig. 3) which are at that moment in the process of digging, is given by the following relation [4]:

$$F_t(\psi) = k_l \cdot l_{sr} \cdot f_o(\psi)\,, \tag{4}$$

$$f_o(\psi) = \begin{cases} \sin\psi \\ (\alpha-\psi)/(\alpha-\pi/2) \\ 0 \end{cases} \qquad \text{for} \qquad \begin{cases} 0 \le \psi \le \pi/2 \\ \pi/2 \le \psi \le \alpha \\ \psi > \alpha \end{cases}$$

where:

k_l - specific resistance to digging for non-homogenous massifs with random character;

l_{sr} - active length of cutting edges of spoons.

This relation was applied to create the algorithm, which can be described in the following way:

1. defining the length of the cutting edges (not discussed here),
2. defining the angular coordinate of the rotor's revolution by using angular velocity ($\psi = \omega \cdot t$),

3. reducing angular coordinate to interval $0^o - 360^o$,
4. defining specific resistance to digging (k_l) as a value with random character,
5. determinaton of resistance to digging of every respective spoon,
6. summing resistances on all spoons which are simulatneously engaged in work on the massif.

Research in this field have shown that specific resistance to digging k_l can be mathematically described by using the nominal law of distribution [5]. The following table gives a review of mean values and standard deviation of value k_l obtained experimentally by measuring on bucket wheel excavator SRs 470. 20.3. at Kosovo coal basin (the measurement was done by 'Lauchhamer' company, who are manufacturers of the above-mentioned bucket wheel excavator).

Digging work environment	Mean value k_l [N/mm]	Standard deviation
Fault zone	436	104
Transitional zone	610	107
Gray clay	692	158

On the basis of this discussion, the values of specific resistance to digging can be simulated by using the existing modules in MatLab software package. This module is relatively simple for use because it automatically generates a number of random numbers according to a pre-given distribution and sample size. With values of specific resistance to digging and supposed size of the active length of cutting edges of spoons obtained in this way, what follows is the block-scheme of the Simulink model for generating resistance to digging of one spoon. The final step is summing of individual resistances so as to obtain total resistance to digging. Simulations obtained in this way are given later in the paper.

4. SIMULATIONS AND ANALYSIS OF OBTAINED RESULTS

Today's level of computer development makes for more certain realization of constructive ideas of certain systems while using data obtained from research on similar objects. However, the possibility to perform adequate calculations within designing itself should also be made use of; those calculations will show what kind of constraint can be expected in the system [6].

Figure 4 shows the change of the force tangent to digging for the first and second spoons. The first figure shows periodic starting of the first spoon's engagement in work with the massif, while the second shows only the second spoon during contact with the massif. It is easily noticeable that the time of engagement with the massif is 2,6 s., and that the second spoons starts enagagement one second later. Figure 5 provides simultaneous change of total resistance to digging as a sum of all resistances on all spoons. All these simulations were performed by means of equation (4) and MatLab software.

By means of known motor excitation (Fig. 2) and defined disturbance of the change of total resistance to digging defined through disturbance of total resistance to digging (Fig. 5), with an equivalent elastic-kinetic and mathematical model (Fig. 1.b), the change of the torsion moment $M_t = f(t)$ of the input shaft of the mechanism's power gear (Fig.1.a), was obtained in MatLab, in the way shown in Fig.6.

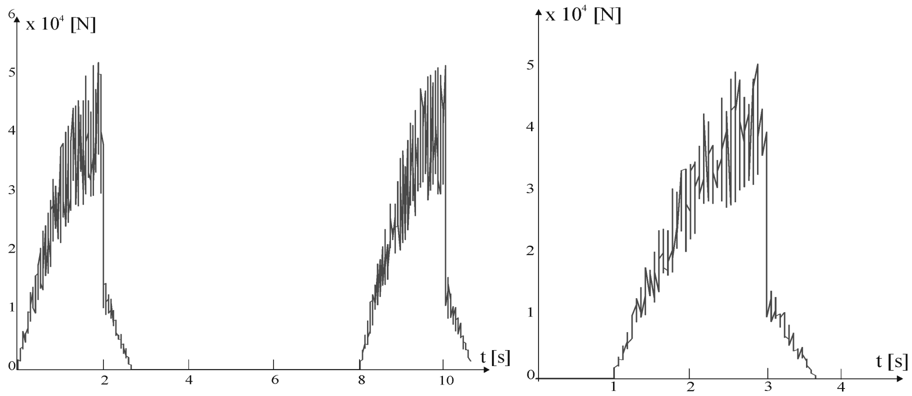


Fig. 4. Change of resistance to digging: a) of the first spoon b) of the second spoon

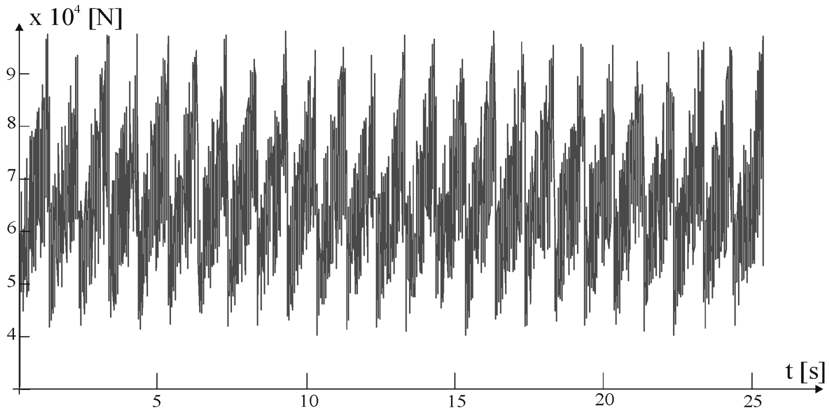


Fig. 5. Change of total resistance to digging

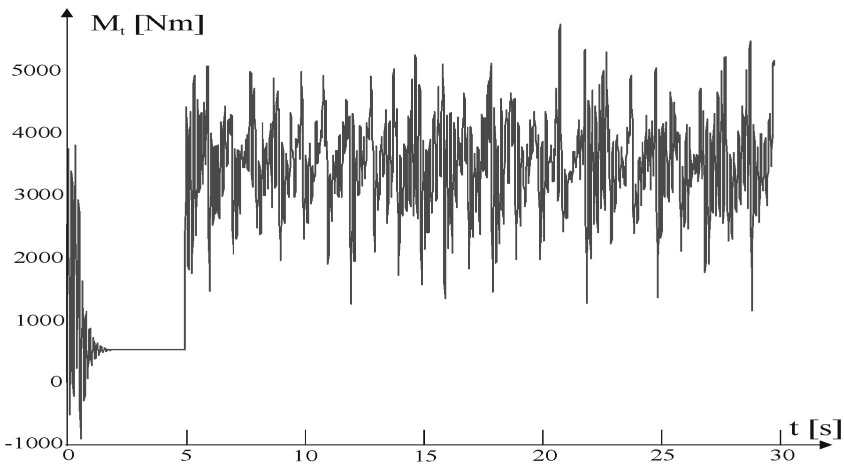


Fig. 6. Change of the twisting moment of the power gear's input shaft

4. CONCLUSION

On the basis of this discussion, it can be concluded that nowadays, when there is advanced software –such as Matlab- at one's disposal, one can solve highly complex non-linear problems. In the concrete case of this paper, what was modelled were the motor's non-linear curve, random process of resistance to digging, and change of the torsion moment depending on the motor's curve and resistance to digging.

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Remark: *The paper was written as a part of the project MIS 3.07.0081 [6].*

SPOLJAŠNJE POBUDE I POREMEĆAJI KOD ROTORNIH BAGERA KAO NELINEARNE I SLUČAJNE FUNKCIJE

Goran Petrović, Vinko Jevtić, Melanija Mitrović, Zoran Marinković

U radu su na primeru pogonskog sistema radnog točka konkretnog roto bagera analizirani spoljašnji uticaji koji potiču od elektromotora i od otpora kopanju kašika. Razmatrane su i analitički modelirane krive momenta puštanja u rad trofaznih asinhronih kaveznih elektromotora kao nelinearne funkcije ugaone brzine $M = f(\dot{\varphi})$. *Pošto je otpor kopanja neujednačen, zbog naizmeničnog manjeg broja kašika u zahvatu sa nehomogenim masivom tla i različitim uglovima zahvata, on se modelira kao slučajna funkcija vremena. Za navedene poremećaje data je i grafička interpretacija. Poznavanje realnijih promena ovih poremećaja omogućava adekvatnije proračune roto bagera koji će biti više iskorišćeniji u eksploataciji.*