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MODELING OF BUCKET WHEEL EXCAVATOR: THEORY AND EXPERIMENTAL RESULTS

UDC

Branislav Jevtović[1], Miroslav Mataušek[2]

[1]Business School, Kosovo Polje-Blace, [2]Faculty of Electrical Engineering, Belgrade

Abstract. *From the viewpoint of designing and tuning an efficient control system, the bucket wheel excavator is a very complex nonlinear plant. To satisfy stringent technical and economic demands the control system must be based on a hierarchical concept, including efficient solution of the basic control level as well as the higher control level. The higher control level must include predictive control, gain scheduling and reference calculations. To design and tune such a complex control system an extremely good nonlinear model of the plant is necessary. The problem of modeling bucket wheel excavator is considered in detail in this paper. First, the functional model is presented. Then, a complete mathematical model is developed. Two sensors, for circular and translator movement of the bucket wheel excavator, are designed and realized, in order to obtain adequate measurements. Free parameters in the mathematical model are obtained by identification. Simulation and experimental results presented here confirm that the nonlinear model obtained captures all the essential dynamic characteristics of the bucket wheel excavator.*

Key Words: *Modeling, Bucket Wheel Excavator, Sensors, Control System*

1. INTRODUCTION

The bucket wheel excavator (BWE) is a complex nonlinear electro-mechanical system, of great mass, dimensions and power. Development and realization of an efficient control system of such a plant requires a good model. First, because of safety reasons it is not possible to adjust the control system by using an experimental trial-and-error tuning procedure. Second, and this is even more important, the design of a new control system must be based on a nonlinear model which captures all the essential dynamic characteristics of such a plant.

In this paper the problem of modeling BWE SRs-1200 (Fig. 1) is analyzed in detail, including a detailed analysis of disturbances acting in different operating regimes. To be practically useful, i.e. to make possible the inclusion, in real-time, the gain-scheduling and

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predictive modes of control, the model must be developed in a trade-off between exactness and simplicity. Finally, development and realization of the high performance sensors for circular and translating movements of the BWE are presented.

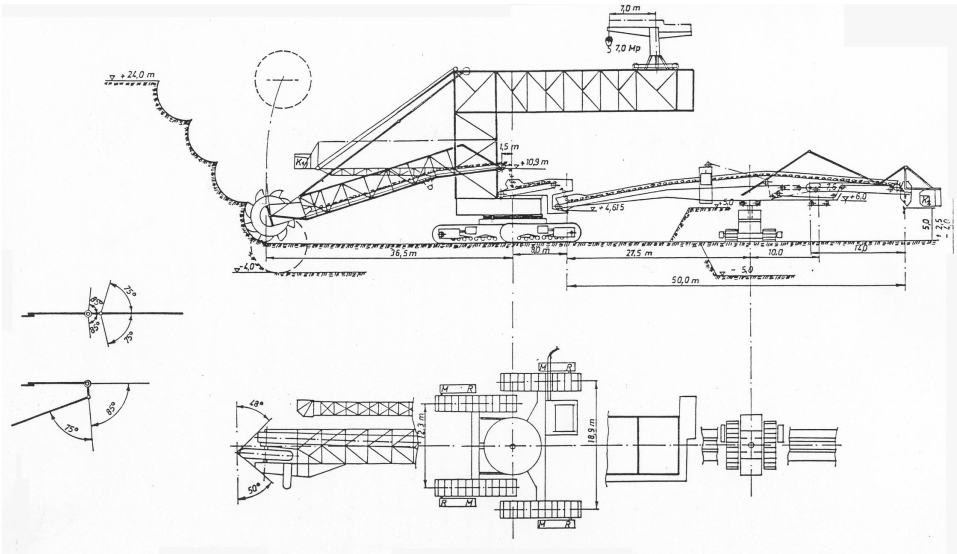


Fig. 1. The Bucket Wheel Excavator SRs-1200

2. FUNCTIONAL MODEL

Circular movement of the super-structure in Fig. 1, from the viewpoint of high efficiency and capacity as well as of safe and reliable operation, is the most important one. The super-structure includes all the components presented in Fig. 1 except transport crawlers and discharged boom. Movement is realized by Ward-Leonhard group with two DC motors (M_1 and M_2, each of 17 kW power). The super-structure considered in this paper, consisting of an electro-mechanical and a mechanical system, is presented in Fig. 2 and Fig. 3. In Fig. 3 the left part includes bucket wheel, its drive and gear mounted at the end of a long bucket wheel boom. On the same figure the right part, consists of counterweight, mounted at the end of a long boom, and swinging platform and plant operator cabin. In respect to the circular movement of the whole super-structure, induced by the moment M_m, there is a relative movement of the left and right parts in Fig. 3, both acting as two pendulums. The left part oscillates with natural period $T_r = 2.5$ s, while the right part oscillates with natural period $T_p = 9.47$ s. It should be noted here that the oscillations of the left part are strictly in the horizontal plane, while the right part oscillations mainly perform in the vertical plane. According to this, and taking into account great masses and long booms, dynamics of the super-structure is a very complex one. To avoid overload of BWE components and accidental situations, raise-time of the cutting speed in horizontal plane is constrained by "dumping machine" (PM).

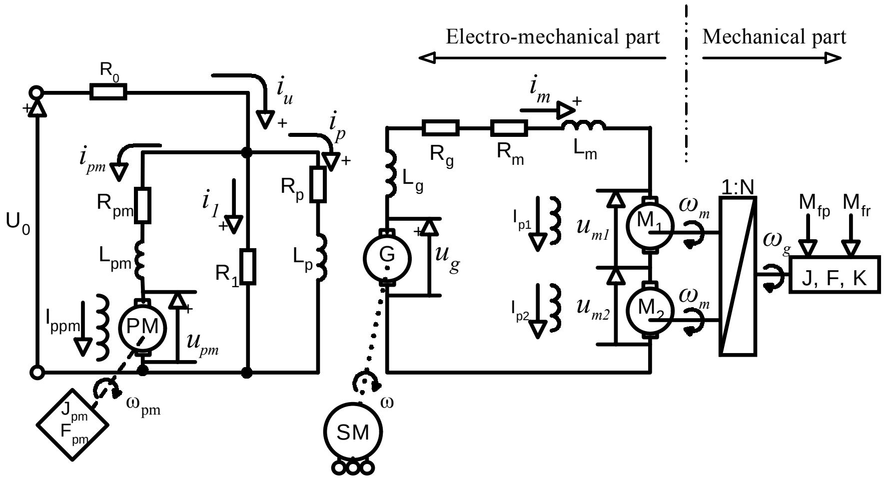


Fig. 2. The Principal Scheme of Super-structure

The control input is current i_u, which is determined by changing the resistor R_{oi} (with constant voltage U_o) as in Fig. 2 or by applying some power electronic equipment. Measurable variables are angular speed ω_m and armature current i_m. Disturbances are defined by mechanical moments M_{fr} and M_{fp}. They can be determined by measuring the bucket wheel motor current and are quite different in different cutting conditions and areas of excavation.

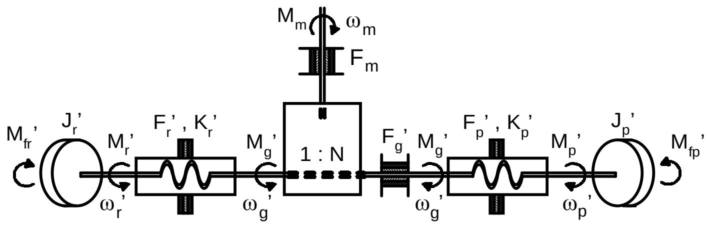


Fig. 3. Simulation Model of the Mechanical Part of Super-structure.

Left and right parts present bucket wheel and counter-weight booms, respectively.

3. MATHEMATICAL MODEL

The state space representation of mathematical model is used to obtain better insight into dynamic behavior of the plant. Differential equations in general form are defined by:

$$\frac{dx}{dt} = Ax + Bu + Ez \tag{1}$$

$$y = Cx \tag{2}$$

where $dim\, x = 5$, $\dim u = 1$, $\dim z = 2$ and $\dim y = 2$. The linearized model (1)-(2) is obtained through detailed analysis of the previously presented nonlinear electro-mechanical system in [4]. State vector, control input, disturbances and measurable outputs are defined by:

$$x = [i_p \quad \omega_r \quad \omega_p \quad M_{Kr} \quad M_{Kp}]^T \tag{3}$$

$$u = [i_u] \tag{4}$$

$$z = [M_{fr} \quad M_{fp}]^T \tag{5}$$

$$y = [\omega_m \quad i_m]^T \ . \tag{6}$$

The controlled variable is given by $y_1 = \omega_m$. Variables in (3)-(6) are presented in Fig. 2 and Fig. 3. Let it be mentioned here that variables M_{Kr} and M_{Kp} define moments of torsion elasticity. Matrices A, B, E and C are defined as follows:

$$A = \begin{bmatrix} \frac{-q}{T_1} & 0 & 0 & 0 & 0 \\ \frac{K_b \cdot F_r}{J_r} & -\frac{F_r \cdot (F_e + F_p + K_a \cdot F_r)}{J_r \cdot F_{em}} & \frac{F_r \cdot F_p \cdot (1-K_a)}{J_r \cdot F_{em}} & \frac{F_e + F_p + K_a \cdot F_r}{J_r \cdot F_{em}} & -\frac{F_r \cdot (1-K_a)}{J_r \cdot F_{em}} \\ \frac{K_b \cdot F_p}{J_p} & \frac{F_p \cdot F_r \cdot (1-K_a)}{J_p \cdot F_{em}} & -\frac{F_p \cdot (F_e + F_r + K_a \cdot F_p)}{J_p \cdot F_{em}} & -\frac{F_p \cdot (1-K_a)}{J_p \cdot F_{em}} & \frac{F_e + F_r + K_a \cdot F_p}{J_p \cdot F_{em}} \\ K_b \cdot K_r & -\frac{K_r \cdot (F_e + F_p + K_a \cdot F_r)}{F_{em}} & \frac{K_r \cdot F_p \cdot (1-K_a)}{F_{em}} & \frac{K_r \cdot (K_a - 1)}{F_{em}} & \frac{K_r \cdot (K_a - 1)}{F_{em}} \\ K_b \cdot K_p & \frac{K_p \cdot F_r \cdot (1-K_a)}{F_{em}} & -\frac{K_p \cdot (F_e + F_r + K_a \cdot F_p)}{F_{em}} & \frac{K_p \cdot (K_a - 1)}{F_{em}} & \frac{K_p \cdot (K_a - 1)}{F_{em}} \end{bmatrix} \tag{7}$$

$$B = [qK_1 / T_1 \quad 0 \quad 0 \quad 0 \quad 0]^T \tag{8}$$

$$E = \begin{bmatrix} 0 & \frac{-1}{J_r} & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{J_p} & 0 & 0 \end{bmatrix} \tag{9}$$

$$C = \begin{bmatrix} K_b & \frac{F_r \cdot (1-K_a)}{F_{em}} & \frac{F_p \cdot (1-K_a)}{F_{em}} & \frac{(K_a - 1)}{F_{em}} & \frac{(K_a - 1)}{F_{em}} \\ \frac{K_b}{K_{em}} & \frac{F_r \cdot K_a}{K_{em}} & \frac{F_p \cdot K_a}{K_{em}} & \frac{-K_a}{K_{em}} & \frac{-K_a}{K_{em}} \end{bmatrix} \tag{10}$$

Coefficients K_a and K_b are given by:

$$K_a = \frac{K_{em} \cdot K_{me}}{R_m \cdot (F_e + F_r + F_p) + K_{em} \cdot K_{me}} \tag{11}$$

$$K_b = \frac{K_g \cdot K_{em} \cdot (F_e + F_r + F_p)}{R_m \cdot (F_e + F_r + F_p) + K_{em} \cdot K_{me}} \ . \tag{12}$$

Coefficients K_1 and T_1 are static gain and time-constant related to the current i_p, while K_g, K_{me} and K_{em} are coefficients related to the generator (G in Fig. 2) and an equivalent motor M (representing motors M_1 and M_2 in Fig. 2).

Coefficient F_{em} deserves special attention. It is, in ideal case, defined by $F_{em} = F_e + F_r + F_p$, where $F_e = F_m + F_g$. However, in reality, there is a great gear backlash (D) in the component denoted in Fig. 3 as an equivalent gear (1:N). To include this non-linearity, which is of essential importance to obtain an adequate model, coefficient Fe depends on the operating regime. Defining $\theta_g = \int \omega_m dt$ and $\theta_m = K_1 K_g K_{em} R \,/\, (R_m F_m + K_{em} K_{me}) \int (1 - e^{-t/T_1}) i_u dt$ two operating regimes could be specified [4]. Due to above mentioned oscillations of the mechanical part of super-structure in Fig. 3 motor M is coupled with the super-structure or decoupled from it. In the last case the motion of the super-structure is driven by inertia. Then $q = 0$ in (7)-(8) and $F_e = F_g$ in (7) and (10)-(12). The coupled case is defined by condition $|\theta_m - \theta_g| = D$, while decoupled case is defined by $|\theta_m - \theta_g| < D$. Accordingly, even if the simplified model is used, as in the present paper, it is nonlinear because its parameters and even structure are abruptly changing during the time.

4. Sensors and measurements

A high performance control system of BWE requires high precision measurements of both circular and translator movements. Due to surrounding conditions and safety, these sensors must be highly reliable. To satisfy these requirements, a sensor of circular movement of special type of rotary encoder with resolution 0.5^o and measurement's scale $\alpha \in [-90^o, +90^o]$, forming a modified version of 9 bits Gray's code, is developed and implemented in [4]. A reduced view of the realized encoder's disc is shown in Fig. 4.

Fig. 4. Encoder's Disc

The application of a modified Gray's code and adequate hardware resulted into a decoder, which enables a reliable auto-detection of most probable cause of malfunction: damage of light sources in a encoder, disc with code rings, light detectors, signal transfer lines or even hardware in decoder itself. Due to these properties this sensor was included also into signalization system of BWE.

By applying the same concept, a high precision and reliable sensor for translator movement of BWE is developed and implemented. Based on a counter-type encoder, the sensor guarantee resolution of 1 cm. A high robustness in respect to the measurement errors induced by mechanical vibrations is confirmed.

5. IDENTIFICATION

Parameters K_1 and T_1 are determined by applying linear system identification method based on generalized error equation, by measuring input i_u and output i_p.

Parameters K_g, R_m, K_{me} and K_{em} are obtained using nominal characteristics of generator and motor and measurements from real system [4].

Parameters F_r, F_p, K_r and K_p are determined indirectly, using, well known relations, describing mechanical oscillating systems: $F_x / J_x = 2\xi_x\omega_x = 2\xi_x 2\pi/T_x$ and $K_x / J_x = \omega_x^2 = (2\pi/T_x)^2$, where $x = r$ for mechanical system of bucket wheel and $x = p$ for mechanical system of counter-weight. Based on these relations, by measuring natural oscillation periods T_r and T_p on the plant and by determining dumping factors ξ_r and ξ_p from measurements of i_m in a different operating regimes, all unknown parameters are determined except for only two – moments of inertia J_r and J_p. These parameters are determined by iterative method, starting from very rough data obtained from disposition of great masses of BWE, and corresponding booms [4] [1].

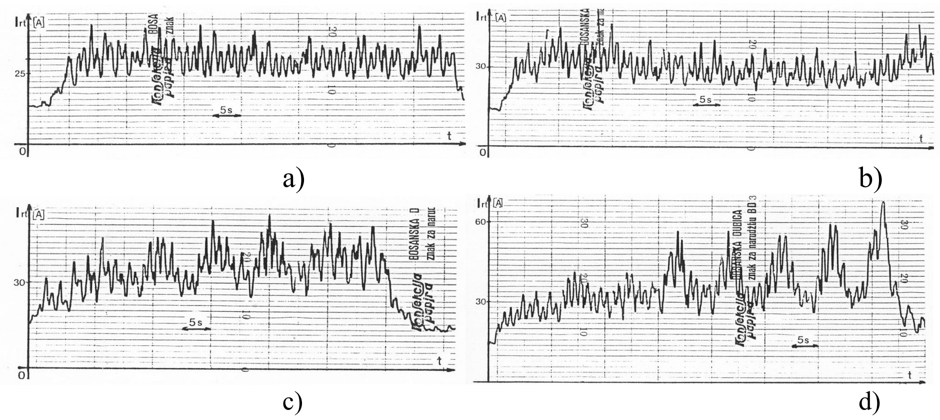


Fig. 5. The bucket wheel motor current when BWE is working in:
a) technological regular cut with cutting effect,
b) technological regular cut with patting effect,
c) technological irregular cut,
d) technological irregular cut with forbidden high cutting parameters.

Finally, to make possible detailed simulation of the plant, disturbances is $M_{fr}(t)$ and $M_{fp}(t)$ are characterized by the following relations:

$$M_{fr}(t) = K_1 \cdot V_k \cdot [1 + K_3 \cdot \sin(\omega_r t)] \cdot [1 + K_5 \sin(2\pi\ T_{rt}^{-1} t)] \tag{13}$$

$$M_{fp}(t) = K_2 \cdot V_k \cdot [1 + K_4 \cdot \sin(\omega_p t)] \cdot [1 + K_5 \sin(2\pi\ T_{rt}^{-1} t)] \tag{14}$$

which are a good representation of the stochastic nature of these disturbances. Parameters K_1, K_2, K_3, K_4 and K_5, as well as period T_{rt} = 1.25 s are determined by measuring the bucket wheel motor current when BWE is working in different cutting regimes, see Fig. 5.

6. EXPERIMENTAL RESULTS

Model responses compared with measurements on real system are presented in Fig. 6. for three typical BWE's operating regimes:

a) regular cut, as mod in which BWE is mostly used,
b) irregular cut, as mod in which BWE is relatively rarely used, when excavating first layer,
c) irregular cut, which is from safety reasons is almost inadmissible.

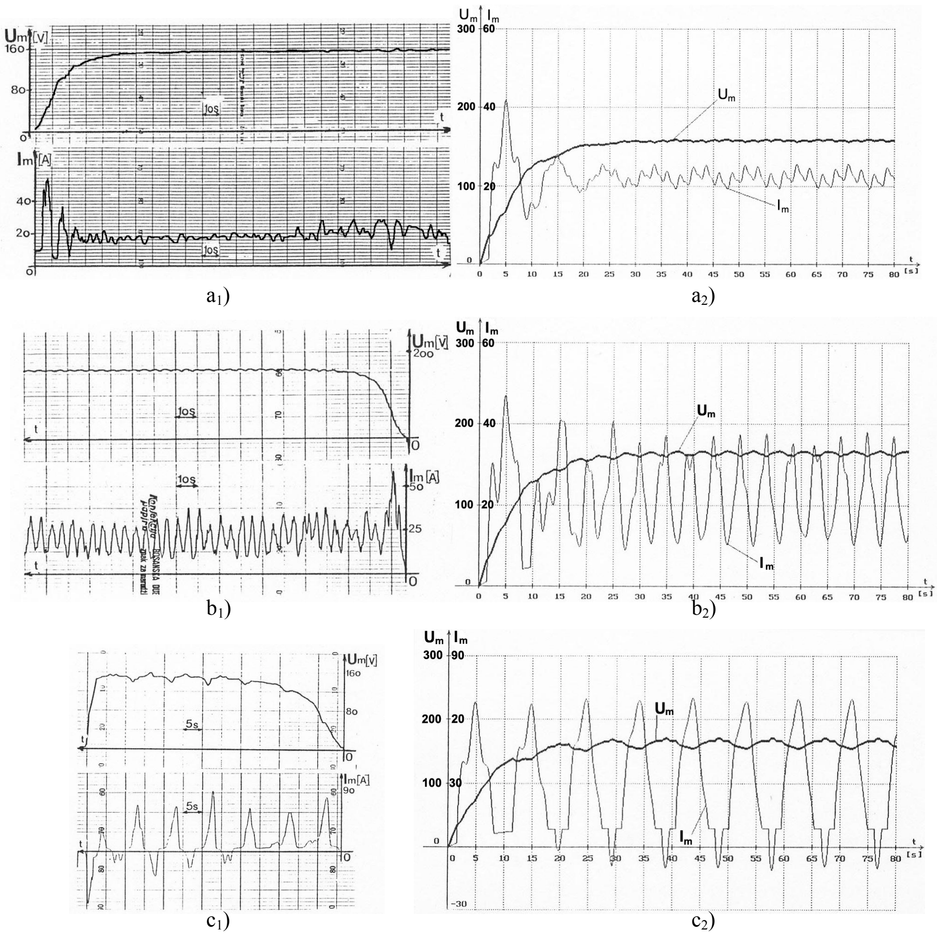
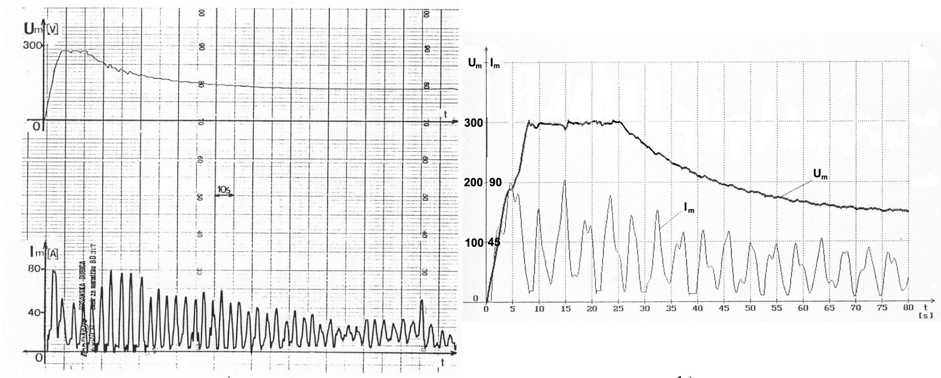


Fig. 6. The comparison of step responses of motor voltage (U_m) and current (I_m):
a_1), b_1) and c_1) measurement,
a_2), b_2) and c_2) model.

Analysis of the last mode has no practical value. This operating regime is considered to obtain an additional verification of the model developed including disturbances, even in this critical operating conditions.

Finally, the validity of the model is demonstrated in Fig. 7, where the results obtained by using the model are compared to the results obtained from the closed-loop experiment. It should be observed here that the current i_m in Fig. 7-b) is obtained as superposition of state-variables, as defined by relation (2), $i_m = y_2$, while in Fig. 7-a) this is a measured current.



a) b)

Fig. 7. Voltage (U_m) and current (I_m) obtained:
a) from closed-loop experiment, b) by using the model.

7. CONCLUSIONS

A general model of BWE is developed with parameters that have a clear physical interpretation. The model is defined in state-space form describing thus the most important variables of the real system.

Special attention is devoted to disturbance modeling, enabling the user to make possible their characterization for various operating regimes, by adjusting only few parameters using available measurements.

Comparison with experimental data, obtained from a real BWE SRs-1200, confirmed the validity of the model, for different operating regimes. Based on this model an efficient tuning of the control system parameters is performed, requiring only small additional readjustment on the real plant.

In BWE, error in measuring circular and translator movement is not acceptable because it can lead to overload of electro-mechanical equipment and even to accidental situations. Developed and implemented sensors beside high precision and reliability, provide alarming and diagnostics of eventual malfunctions.

Development of BWE hierarchical adaptive-predictive control system is in progress. Based on available measurements this system determines excavating material characteristics, enabling us to predict the desired reference for circular movement and to adapt control system parameters to a large the capacity of BWE and to make possible the continuous excavation. Partially, this concept has already been realized.

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MODELIRANJE ROTORNOG BAGERA – BAGERA GLODARA: TEORIJA I EKSPERIMENTALNI REZULTATI

Branislav Jevtović, Miroslav Mataušek

Rotorni bageri – bageri glodari su, sa stanovišta projektovanja i podešavanja efikasnog sistema upravljanja, veoma kompleksni nelinearni objekti. U cilju zadovoljenja strogih tehničkih i ekonomskih eksploatacionih zahteva sistem upravljanja mora biti zasnovan na hijerarhiskom konceptu, uključujući efikasna rešenja kako na baznom, tako i na višem hijerarhijskom nivou upravljanja. Viši nivo upravljanja mora da sadrži prediktivno upravljanje, podešavanje parametara i odredjivanje reference. Da bi bilo moguće projektovati ovako kompleksan sistem upravljanja, neophodno je posedovati izuzetno dobar nelinearni model objekta upravljanja. U ovom radu će detaljno biti opisan problem modeliranja rotornih bagera – bagera glodara. Prvo će biti prezentovan funkcionalni model. Zatim, razvoj kompletnog matematičkog modela, kao i dva senzora, kružnog i translatornog kretanja, koji su razvijeni i realizovani u cilju dobijanja preciznih merenih veličina u veoma nepovoljnim uslovima rada – uopše posmatrano. Slobodni parametri matematičkog modela su dobijeni identifikacijom. Prezentovani rezultati simulacije i eksperimentalnih rezultata potvrdjuju da je razvijeni nelinearni model u toj meri zadovoljavajući – tj. da opisuje sve važnije dinamičke karakteristike bagera, da je konačno podešavanje parametara sistema upravljanja svedeno na minimalne izmene u odnosu na vrednosti dobijene u simulaciji.