Kinematic and Dynamic Simulation of the Wheel Loaders with the Z-bar Working Mechanism

Dragoslav Janošević,^{1*} Jovan Pavlović¹, Vesna Jovanović¹, Predrag Milić¹

¹University of Niš, Faculty of Mechanical Engineering

This paper presents the mathematical model and program for the kinematic and dynamic analysis of wheel loader with the Z-bar working mechanism. Kinematic analysis determined a linear and angular speed and acceleration of center of mass for the kinematic chain members. Dynamic analysis determined an inertial force and rotational inertia torque of center of mass for the members of kinematic chain of the machine by Newton-Euler dynamic equations. As an example, the results of kinematic and dynamic analysis are given for the wheel loader which mass is 15000 kg and volume of bucket is 2.7 m³.

Keywords: Wheel loaders, kinematic and dynamic analysis

0. INTRODUCTION

The wheel loaders are characterized by the possibility of performing different functions due to different configurations of the working mechanism and the possibility of equipping with various tools.

The main (primary) function of the loader is cyclic (intermittent) transport of a bulk material at a certain distance (up to $l = 50$ m). In general, the basic function of the loader consists of the following partial functions: loading, transport, unloading the materials and return again to a new place of loading.

In this paper is observed general configuration of kinematic chain, that is consists of: rear L_1 (Fig. 1) and front L_2 supporting-moving mechanism and the manipulator with arm L_3 and bucket L_4 . With direct link of pairs of arm hydro-cylinders c_3 for the frame of moving mechanism L_2 and for arm L_3 , is formed drive mechanism of arm.

The drive mechanism of bucket is consists of one or two hydro-cylinders c_4 which are on one side connected with direct link to the frame of moving mechanism L_2 , and from other side is connected, via two-arm lever c_{41} and rod c_5 , to bucket L_4 , thus formed configuration in shape of letter "Z" by which the kinematics of the manipulator is named.

Fig.1. The physical model of wheel loader

1. MATHEMATICAL MODEL

The mathematical model of loader with the Z-bar kinematics is defined to allow the numerical simulation of loader's manipulative task in function of cycle duration. The mathematical model also determine the kinematic and dynamic parameters of the kinematic chain and drive mechanism of machine[1].

The simulation starts from a set of given values:

$$P_u = \{V, b_4, Y_i, \alpha_i, t_c, K_z\} \quad (1)$$

where is: V - volume of bucket, b_4 - width of bucket, Y_i - unloading height, α_i - bucket unloading angle, t_c - time of manipulative task, K_z - subset of the characteristics of the material.

Defined mathematical model of the loader kinematic chain is based on general theorems of mechanics. The members of the loader kinematic chain builds kinematic pairs of fifth class - rotary joint with one degree of freedom. An axes of joints are axes of relative rotation of the members who build the kinematic chain pairs.

The member of loader kinematic chain L_i is determined in its local coordinate system $O_i x_i y_i z_i$ with set of a geometric and dynamic sizes:

$$L_i = \{\tilde{e}_i, \tilde{s}_i, \tilde{t}_i, m_i, \tilde{J}_i\} \quad (2)$$

where is: $\tilde{e}_i$ - orientation of an axis of joint O_i with whom the member L_i is connected to previous member L_{i-1} , $\tilde{s}_i$ - position vector of the joint center with whom the member L_i is connected to forward member L_{i+1} , intensity of vector $\tilde{s}_i$ represents the kinematic length of member, $\tilde{t}_i$ - position vector of center of mass m_i of member chain L_i in absolute coordinate system, $\tilde{J}_i$ - moment of inertia tensor of member.

Values that is tagged with "wave" above the mark, are defined in the local coordinate system of members.

1.1 Kinematic model

The mathematical model of kinematic chain corresponds to the next inner (generalized) coordinates:

$$\theta_i = \{\theta_1, \theta_3, \theta_4\} \quad (3)$$

where is: $\theta_1 = x_1$ - penetration length of bucket, apropos the relative movement of the loader in relation to the surface, θ_3 - relative angle position of arm L_3 relative to the x - axis of the previous member L_2 , θ_4 - relative angle of the bucket L_4 relative to the x - axis of the previous member L_3 .

The generalized coordinates determine position of the members of kinematic chain L_3 and L_4 , relative to an absolute coordinate system, and they are:

$$\varphi_3 = \theta_3 \quad (4)$$

$$\varphi_4 = \theta_3 + \theta_4 \quad (5)$$

The vectors of: position of the center of the joint r_i , the center of mass r_{ti} of kinematic chain members and the center of the cutting edge of the bucket r_w , relative to an absolute coordinate system are determined by the equations:

$$r_i = \sum_{j=1}^{i-1} A_{jo} \tilde{s}_j \quad (6)$$

$$r_w = \sum_{j=1}^4 A_{jo} \tilde{s}_j \quad (7)$$

$$r_{ti} = r_i + A_{io} \tilde{t}_i \quad (8)$$

where is: A_{jo}, A_{io} - transformation matrix for the transformation of a vector from the local to the absolute coordinate system [3].

The transformation matrix of mathematical model:

$$A_{3o} = \begin{vmatrix} \cos \varphi_3 & -\sin \varphi_3 & 0 \\ \sin \varphi_3 & \cos \varphi_3 & 0 \\ 0 & 0 & 1 \end{vmatrix} \quad (9)$$

$$A_{4o} = \begin{vmatrix} \cos \varphi_4 & -\sin \varphi_4 & 0 \\ \sin \varphi_4 & \cos \varphi_4 & 0 \\ 0 & 0 & 1 \end{vmatrix} \quad (10)$$

The work of loader is characteristic in that the manipulative tasks are numerous and cyclic but with the

same operations structure. However, at each cycle, a operation have different parameters. For ease defining, each parameter of the manipulative task is marked with index ij , where index i denotes the number of the kinematic chain member that carrier operations with the index j .

The manipulative task that is analyzed in this paper consists of the following operations:

- loading the material with bucket ($j=1$),
- lifting the material to a certain height ($j=2$), and
- unloading the bucket ($j=3$).

The inner coordinates of operations j of manipulative task corresponds to a specific range of motion of each kinematic chain member L_i :

$$\delta_{ij} = \theta_{ij4} - \theta_{ij1} \quad (11)$$

where is: δ_{ij} - movement range of the members i and the operation j , θ_{ij1} , θ_{ij4} - inner coordinates of the member position L_i , on start $k=1$ and on end $k=4$ of operation j .

For each member L_i of the kinematic chain and for each operation j the phase time are given: a) time t_{ij1} of beginning of the operation and the start of acceleration, b) end time t_{ij2} of acceleration, c) beginning time t_{ij3} of deceleration, d) end time t_{ij4} of operation and end of deceleration. As an example, the inner coordinates of the members L_1 and L_2 at the operation of loading material ($j=1$) are:

$$x_{11} = \begin{cases} x_{111} = 0 \quad \forall t = t_{111} \\ x_{114} = \left(\frac{2V}{b_4 \cdot \tan \varphi_o} \right)^{0.5} \quad \forall t = t_{114} \end{cases} \quad (12)$$

Where is: φ_o - natural angle of material slope.

Fig.2. The mathematical model of wheel loader

The members of the loader's kinematic chain, which are carriers of the certain operations of manipulative task with a known range of motion, given phase times and adopted cycloid change of motion, corresponds to a certain maximum speeds (Fig. 3):

$$\dot{\theta}_{ijm} = \frac{2\delta_{ij}}{(t_{ij3} + t_{ij4}) - (t_{ij1} + t_{ij2})} \quad (13)$$

on the basis of which are determined change of the speed:

$$\dot{\theta}_{ij} = \begin{cases} \frac{\dot{\theta}_{ijm}}{2} \left[1 - \cos \left(\frac{t - t_{ij1}}{t_{ij2} - t_{ij1}} \right) \pi \right] \quad \forall t_{ij1} \leq t \leq t_{ij2} \\ \dot{\theta}_{ijm} \quad \forall t_{ij2} \leq t \leq t_{ij3} \\ \frac{\dot{\theta}_{ijm}}{2} \left[1 + \cos \left(\frac{t - t_{ij3}}{t_{ij4} - t_{ij3}} \right) \pi \right] \quad \forall t_{ij3} \leq t \leq t_{ij4} \end{cases} \quad (14)$$

and acceleration:

$$\ddot{\theta}_{ij} = \begin{cases} \frac{\dot{\theta}_{ijm}}{2} \frac{\pi}{t_{ij2} - t_{ij1}} \sin \left(\frac{t - t_{ij1}}{t_{ij2} - t_{ij1}} \right) \pi \quad \forall t_{ij1} \leq t \leq t_{ij2} \\ 0 \quad \forall t_{ij2} \leq t \leq t_{ij3} \\ -\frac{\dot{\theta}_{ijm}}{2} \frac{\pi}{t_{ij4} - t_{ij3}} \sin \left(\frac{t - t_{ij3}}{t_{ij4} - t_{ij3}} \right) \pi \quad \forall t_{ij3} \leq t \leq t_{ij4} \end{cases} \quad (15)$$

The kinematic values of the kinematic chain members of loaders are: linear v_i and angular velocity ω_i and linear a_i and angular accelerations ε_i of chain member L_i , and they are determine relative to an absolute coordinate system with recursive equations [2][3]:

$$\omega_i = \omega_{i-1} + \dot{\theta}_i \mathbf{e}_i \quad (16)$$

$$\varepsilon_i = \varepsilon_{i-1} + \ddot{\theta}_i \mathbf{e}_i + \dot{\theta}_i (\omega_i \times \mathbf{e}_i) \quad (17)$$

$$\mathbf{v}_i = \mathbf{v}_{i-1} - \omega_{i-1} \times \mathbf{r}_{i-1,i} + \omega_i \times \mathbf{r}_{i,i+1} + \dot{\theta}_i \mathbf{e}_i \quad (18)$$

$$\mathbf{a}_i = \mathbf{a}_{i-1} - \varepsilon_{i-1} \times \mathbf{r}_{i-1,i} - \omega_{i-1} \times (\omega_{i-1} \times \mathbf{r}_{i-1,i}) + \varepsilon_i \times \mathbf{r}_{i,i+1} + \omega_i \times (\omega_i \times \mathbf{r}_{i,i+1}) + \ddot{\theta}_i \mathbf{e}_i + 2\dot{\theta}_i (\omega_i \times \mathbf{e}_i) \quad (19)$$

Fig. 3. Trapezoidal model of motion of the kinematic chain members with cyclical changes of the angular velocity

1.2 Dynamic model

On the members of the loader's kinematic chain, during cycle operation, act internal (gravitational, inertial) and external (technological) loads.

Dynamic values of the member L_i are: inertial force F_i which is determined by second Newton's law:

$$\mathbf{F}_i = -m_i \mathbf{w}_i \quad (20)$$

and rotational inertia torque M_i , which is determined based on Euler's dynamic equations:

$$\tilde{\mathbf{M}}_i = -\tilde{\mathbf{J}}_i \tilde{\boldsymbol{\varepsilon}}_i + \tilde{\boldsymbol{\omega}}_i \times \tilde{\mathbf{J}}_i \tilde{\boldsymbol{\omega}}_i \quad \mathbf{M}_i = A_{i0} \tilde{\mathbf{M}}_i \quad (21)$$

where is: $\tilde{\boldsymbol{\omega}}_i = A_{oi} \boldsymbol{\omega}_i$, $\tilde{\boldsymbol{\varepsilon}}_i = A_{oi} \boldsymbol{\varepsilon}_i$ - angular velocity and angular accelerations of the member L_i in local coordinate system $O_i x_i y_i z_i$, A_{oi} - transformation matrix of the model for transformation of the vector from absolute to local coordinate system

The total force related to the center of mass of member L_i , taking the influence of gravity, is equal to:

$$\mathbf{F}_{ui} = \mathbf{F}_i + m_i \mathbf{g} \quad (22)$$

On separated kinematic chain member L_i (Fig.2) besides the total force F_{ui} and torque M_{iu} is acting also reactions $-F_{ri+1}, -M_{ri+1}$ of forward member L_{i+1} in joint O_{i+1} and force F_{ri} and torque M_{ri} in joint O_i . From the equilibrium conditions of separated member L_i it can be determined force F_{ri} and torque M_{ri} in joint O_i :

$$\mathbf{F}_{ri} = \mathbf{F}_{ci} + \mathbf{W} + \sum_{j=i}^4 \mathbf{F}_{uj} \quad \forall i = 3, 4 \quad (23)$$

$$\mathbf{M}_{ri} = \mathbf{M}_{ci} + (\mathbf{r}_w - \mathbf{r}_i) \times \mathbf{W} + \sum_{j=i}^4 \mathbf{M}_j + \sum_{j=i}^4 (\mathbf{r}_j - \mathbf{r}_i) \times \mathbf{F}_{uj} \quad \forall i = 3, 4 \quad (24)$$

where is: $\mathbf{F}_{ci}$ - force of the hydro-cylinder or two-arm lever of the drive mechanism of member L_i , $\mathbf{W}$ - loading resistances (digging) which is acting in center of the bucket cutting edge O_w and $\mathbf{M}_{ci}$ - torque of drive mechanism for joint O_i . Dynamic torque of drive mechanism are:

$$\mathbf{M}_{oi} = \mathbf{M}_{ri} \cdot \mathbf{e}_i \quad (25)$$

1.2.1. Digging resistances.

The external (technological) loads during operation of material loading, occurs in the form of loading resistances (digging) of material. The material loading operations is usually performed thus the bucket first penetrate into a pile of material by movement of the loader, and then comes to filling the bucket by rotation of bucket around the arm top. In horizontal penetration of the bucket when loader's speed is v (Fig. 4), there are the following components of loading resistance (digging): resistances along the horizontal cutting edge W_{x1} , resistances along the vertical cutting edge W_{x2} , the frictional resistances of the affected material on the bottom of the bucket W_{x3} , resistances to friction of inner and outer sides of the bucket W_{x4} , the frictional resistance of the outer surface of the bottom of the bucket W_{x5} , friction resistance of material on the bottom of the bent part of bucket W_{x6} . Resistance W_{x1} along the horizontal cutting edge [7]:

$$W_{x1} = k_x \cdot b_4 \cdot x_l \quad (26)$$

where is: k_x - specific resistance of the materials at bucket penetration [kN/m^2], x_l - current distance from the top of the bucket cutting edge to the bottom of material pile (length of penetration) [m], W_{x1} - resistance [kN].

Resistances W_{x2} along the vertical cutting edge:

$$W_{x2} = \frac{l}{2} k_x \cdot h \cdot x_l = \frac{l}{2} k_x \frac{\tan \varphi_o \cdot \tan \beta}{\tan \varphi_o + \tan \beta} \cdot x_l^2 \quad (27)$$

where is: h - slice thickness, β - tip angle of bucket side profile.

The current slice thickness h of the material can be determined from equation (Fig. 4a):

$$h = e \cdot \tan \beta = (x_l - e) \tan \varphi_o \quad (28)$$

from which follows:

$$e = \frac{x_l \cdot \tan \varphi_o}{\tan \varphi_o + \tan \beta} \quad (29)$$

so when the values of e is transform in equation 27 we have:

$$h = \frac{x_l \cdot \tan \varphi_o \cdot \tan \beta}{\tan \varphi_o + \tan \beta} \quad (30)$$

The resistances W_{x3} of frictional of the affected material on the bottom of the bucket:

$$W_{x3} = \mu_2 \iint_{A_d} p_d \cdot dA_d \quad (31)$$

where is: μ_2 - coefficient of material friction on the metal, p_d - the pressure of the affected material to the surface A_d of the bottom part of the bucket.

Pressure p_d at the elementary surface $dA_d = b_5 \cdot dx$ have value (Fig.4c):

$$p_d = g \rho_z x_l \cdot \tan \varphi_o (1 + \sin^2 \varphi_o) \quad (32)$$

Substitution of expressions for p_d and dA_d in equation (2.48) we get:

$$W_{x3} = \frac{l}{2} \mu_2 \cdot b_4 \cdot g \rho_z \cdot \tan \varphi_o (1 + \sin^2 \varphi_o) x_l \quad (33)$$

where is: ρ_z - density of the affected materials [kg/m^3], b_5 - bucket width [m], W_{x3} - resistance [N].

The frictional resistance W_{x4} of the affected materials on the inner surface of the side sheet metal of bucket:

$$W_{x4} = \mu_2 \iint_{A_b} p_b \cdot dA_b = \mu_2 \cdot p_{b5} \cdot A_b \quad (34)$$

where is: p_b - lateral pressure of the affected materials on the elementary side surface dA_b which covers the affected material inside the bucket, p_{b5} - medium pressure to the total lateral surface A_b , which covers the affected material.

Medium pressure p_{b5} corresponding one third of the material pressure p_{bo} in point O_w (Fig. 4a):

$$p_{b5} = \frac{1}{3} p_{bo} = \frac{1}{3} g \rho_z \cdot x_l \cdot \tan \varphi_o (1 + \sin^2 \varphi_o) \cdot \tan^2 \left(\frac{\pi}{4} - \frac{\rho}{2} \right) \quad (35)$$

Where is: ρ - internal angle of friction of materials.

Fig.4. Digging resistance of bucket: a) components of resistance at bucket penetration, b) components of resistance at bucket filling, c) pressure distribution of material on the bucket internal side

Total current lateral surface:

$$A_b = \frac{l}{2} x_l \cdot h = \frac{tg \varphi_o \cdot tg \beta}{2(tg \varphi_o + tg \beta)} x_l^2 \quad (36)$$

Substitution of equations (35) and (36) into equation (34) it is obtained resistance W_{x4} :

$$W_{x4} = \mu_2 \frac{g \cdot \rho_z \cdot tg \beta \cdot tg^2 \varphi_o \left[(1 + \sin^2 \varphi_o) \cdot tg^2 \left(\frac{\pi}{4} - \frac{\rho}{2} \right) \right]}{6(tg \varphi_o + tg \beta)} x_l^3 \quad (37)$$

The frictional resistance W_{x5} of the outer surface of the bottom of the bucket on material is equal:

$$W_{x5} = W_{x3} \quad (38)$$

If at penetration the bucket rely with its weight on the surface. In the case of bucket penetration, when arm is carrying the bucket this resistance does not exist:

$$W_{x5} = 0 \quad (39)$$

The resistance W_{x6} of material friction on the bottom of the folded portion of the bucket occurs if $x_l > L_4$:

$$W_{x6} = 2 \cdot g \rho_z \cdot b_4 \cdot tg \varphi_o \cdot tg^2 \left(\frac{\pi}{4} + \frac{\varphi_o}{2} \right) \cdot (x_l - L_4)^2 \quad (40)$$

where is: L_4 - the distance from the tip of the cutting edge to the bottom of the bucket.

The total resistance W_x of bucket penetration:

$$W_x = W_{x1} + 2W_{x2} + W_{x3} + 4W_{x4} + W_{x5} + W_{x6} \quad (41)$$

At the end of the penetration, by turning the bucket around the arm top, with angular velocity ω (Fig.4b) it comes to the bucket filling while it occurs following vertical resistance: slippage resistance of the affected material's prisms on the frontal plane of massif W_{y1} , slippage resistance of affected material prism to the vertical side of massif W_{y2} , penetration resistance of the side edges of bucket W_{y3} , friction resistance of prism to the inner and outer side of the plates W_{y4} , vertical load of the prisms on the bucket bottom W_{y5} .

The slippage resistance W_{y1} of the affected material's prisms on the frontal plane of massif:

$$W_{y1} = g \rho_z \left[b_4 + x tg \varphi_o \cdot tg \left(\frac{\pi}{4} - \frac{\rho}{2} \right) \right] \frac{tg \varphi_o \sin^2 \varphi_o}{2} x_l^2 \quad (42)$$

The slippage resistance W_{y2} of affected material prism to the vertical side of massif:

$$W_{y2} = g \rho_z \frac{tg^3 \varphi_o}{6(tg \varphi_o + tg \beta)} (1 + \sin^2 \varphi_o) \cdot tg \left(\frac{\pi}{4} - \frac{\rho}{2} \right) x_l^3 \quad (43)$$

The penetration resistance W_{y3} of the side edges of bucket:

$$W_{y3} = \frac{W_{x2}}{tg \beta} \quad (44)$$

The friction resistance W_{y4} of prism to the inner and outer side of the plates:

$$W_{y4} = W_{x4} \quad (45)$$

The total vertical load of the affected material's prism on bottom of the bucket:

$$W_{y5} = \frac{W_{x3}}{\mu_2} \quad (46)$$

The total vertical resistance of bucket filling:

$$W_y = W_{y1} + 2W_{y2} + 2W_{y3} + 4W_{y4} + W_{y5} \quad (47)$$

2. PROGRAM

Based on predefined mathematical model a program (Fig. 4), was developed which provides a detailed kinematic and dynamic analysis of the wheel loader, by simulation of given manipulative tasks.

As an example, using the developed software, kinematic and dynamic analysis of kinematic chain members of wheel loaders with Z-bar manipulator, was performed, mass of loader is 15000 kg and a volume of bucket is 2.7 m³.

Simulated manipulative task, consisted of next operations: loading of material, lifting the affected material and unloading at a given height.

In this paper, as part of a kinematic analysis, there are given diagrams (Fig. 7) of changes of next values: generalized coordinates x_l, θ_3, θ_4 (Fig. 7a) of the kinematic chain of loader, the components of linear velocity v_{4x}, v_{4y} (sl.7b) and angular velocity ω_{4z} and linear acceleration components a_{4x}, a_{4y} (sl.7c) and angular acceleration ε_4 of bucket.

Fig.5. Algorithm of developed program for kinematic and dynamic analysis of the wheel loader

The changes of generalized coordinates of kinematic chain members (Fig. 6a) show that at loading it comes to simultaneous movements of the moving mechanism members L_1 and L_2 and the bucket rotation L_4 . The operation of lifting a loaded material on given height is accomplished by movement of arm L_3 and depending on movement of bucket L_4 . Bucket rotation, while arm is lifting, occurs because the drive mechanism of bucket is dependent on drive mechanism of arm with aim to maintain the bucket in a position where there is no spilling materials when arm is lifting. Unloading operations are carried out only by running buckets.

Analysis of changes of the speed and acceleration shows that the largest changes in angular velocity ω_{4z} (Fig. 6 b) and angular acceleration ε_{4z} (Fig. 6c) has the bucket at the beginning and at the end of lifting operation, when comes to correction of the bucket that no spilling of materials.

As part of the dynamic analysis there are given diagrams (Fig. 7) of the next changes of values: components of inertial forces of bucket F_{4x} , F_{4y} (Fig. 7) and the affected material F_{2x} , F_{2y} , inertial torques of arm M_3 (Fig. 7b), bucket M_4 and affected materials M_2 , static and dynamic load torque of the arm drive mechanism M_{03s} , M_{03} (sl.7c) and static and

Fig.6. Kinematic analysis of wheel loader: a) change of generalized coordinates, b) components of linear v_4 and angular velocity ω_4 , c) components of linear a_4 and angular accelerations ε_4

Fig.7. Dynamic analysis of wheel loader: a) change of inertial force, b) change of rotational inertia torque components, c,d) static and dynamic load torques of drive mechanism of arm and bucket

dynamic load torque of drive mechanism of bucket M_{o4s} , M_{o4} (Fig. 7d).

To sudden changes of components of inertial forces of the bucket and affected material occurs at the beginning and end of the transport operation of the affected material. At the beginning of transport operations of material, at lifting of the arm manipulator, the horizontal component of the force of inertia of the affected material has the highest value of variable directions (Fig. 7a). At the end of the operation as the largest force, occurs the vertical component of the inertial force of the affected material (Fig. 7a). Minor changes in inertial forces generated at the end of the operation of loading and at the beginning of the operation of unloading the bucket due to changes in the masses of the affected material.

Extremely variables of the inertial torque of arm, bucket and affected materials also occur at the beginning and end of the operation of the material transport, and the biggest occurring inertial torques are inertial torques of arm and bucket (Fig. 7b).

The analysis of torque of drive mechanism of arm and bucket shows that the largest load torque of mechanisms occur during the operation of materials loading when the difference of static and dynamic load torque is negligible, knowing that the process of loading of material is comparatively slow. Substantial differences of static and dynamic torque load drive mechanism occurs at the beginning of the transport operation and at the operation of unloading of materials due to sudden changes in the mass of the affected material.

3. CONCLUSION

In the development of wheel loaders is necessary kinematic and dynamic analysis of kinematic chain members and drive mechanisms of the machine. For these reasons, here are developed a mathematical model and program for detailed kinematic and dynamic analysis of all members of the kinematic chain during simulated manipulative task which consists of operations: loading, transport and unloading of materials. Mathematical model is based on *Newton- Euler* dynamic equations.

The developed model and software enable that on given sets of manipulative task we can defined: linear and angular velocity and acceleration, the inertial forces and inertia torques of the center of mass of each member of kinematic chains and load torque of drive mechanism of the machine. Kinematic and dynamic parameters that are obtained by simulation presents the basis for defining the structure of kinematic chain members and optimal synthesis of drive mechanism of loader.

4. ACKNOWLEDGEMENT

This paper is result of technological project No. TR35049, supported by Ministry of Education, Science and Technological Development of the Republic of Serbia

5. REFERENCES

- [1] Janošević, D. "Projektovanje mobilnih mašina", Faculty of Mechanical Engineering University of Niš, 2006.
- [2] Dresig, H. and Holzweissig, F. "Dynamics of machinery", Springer, Berlin, London, 2010.
- [3] Potkonjak, V. "Robotika", Naučna knjiga, Belgrade, 1989.
- [4] Brach, I. and Tyro G. "Maszyny ciagnikowe do robot ziemnych", Wydawnictwa Naukowo - Techniczne, Warszawa, 1986.
- [5] Jovanović, V., Janošević, D., and Pavlović J. "Experimental determination of resistance digging of hydraulic excavator", IMK-14-Research & Development in Heavy Machinery 19(3), pp. 83-88, 2013.
- [6] Shen, J., Wang, G., Bi, Q., and J. Qu "A comprehensive genetic algorithm for design optimization of Z-bar loader working mechanism". Journal of Mechanical Science and Technology Vol.11, No.27, pp. 3381-3394, June 2013.
- [7] Pavlović, J., Jovanović M., and Milojević, A. "Optimal synthesis of the manipulator using two competitive methods" Facta universitatis Series: Mechanical Engineering Vol. 12, No 1, pp. 61 - 72, 2014.
- [8] Pavlović, J., Janošević, D., Jovanović, V., Milić, P. "Dynamic analysis of the Z-bar loader working mechanism" in proc. The Fifth International Conference TRANSPORT AND LOGISTICS TIL 2014, pp. 119-123, Niš, 2014.
- [9] Filla, R. "Quantifying Operability of Working Machines", Linkoping Studies in Science and Technology Dissertations, No 1390, Linkoping 2011.
- [10] Filla, R. and Palmberg, J. O. "Using Dynamic Simulation in the Development of Construction Machinery". The Eighth Scandinavian International Conference on Fluid Power, Tampere, Finland, Vol.1, pp. 651-667, May 7-9, 2003.
- [11] Filla, R. "An Event-driven Operator Model for Dynamic Simulation of Construction Machinery". The Ninth Scandinavian International Conference on Fluid Power, Linkoping, Sweden, June 1-3, 2005.
- [12] Worley, M. D. and La Saponara, V. "A simplified dynamic model for front-end loader design" Proc. IMechE Vol. 222 Part C: J. Mechanical Engineering Science, SAGE, pp. 2231-2249, 2008.