WEB BASED ENVIRONMENT FOR DESIGN AND ANALYSIS OF HYDRAULIC EXCAVATOR

Rosen MITREV
Mechanical Engineering Faculty
Technical University-Sofia
Bulgaria
rosenm@tu-sofia.bg

***Abstract*— The present paper is devoted to the development of computational algorithms for design and analysis of hydraulic excavator. The position analysis of the equipment is based on matrix description of the position of the links, which forms the equipment open kinematic chain. The static force analysis is performed after position analysis and is used for determination of the static reactions in the equipment joints. The developed algorithms are implemented in the web based environment for design and analysis.**

Keywords—web based environment, hydraulic excavator, position and staic force analysis

I. INTRODUCTION AND OBJECTIVE OF THE STUDY

The hydraulic excavators are widely used for digging processes in construction, for geotechnical and mining operations. They consists of travelling base machine and front digger. The front digger consists of boom, stick and bucket driven by hydraulic cylinders. From the kinematical point of view, the front digger represents an open kinematic chain, consisting of bodies, connected by joints. The hydraulic cylinders and the front digger links forms closed loop contours, mostly three rocker mechanisms and a four-bar mechanism. The basic structural components of the excavator are shown at Fig.1.

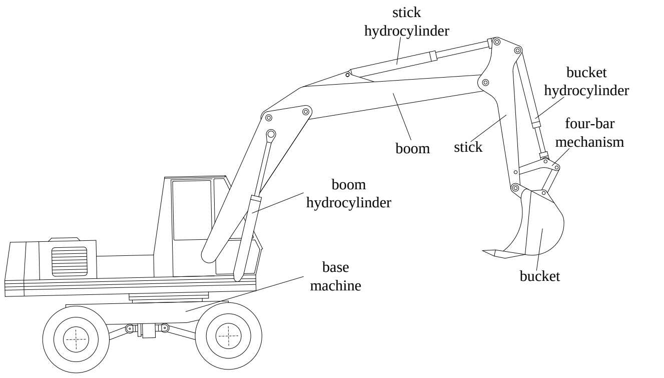


Fig.1 Basic structural components of the hydraulic excavator

The design of a hydraulic excavator is a complex and multidisciplinary activity. There are vast of papers which deals with the different aspects of the design and behavior of the excavators in the real exploitation conditions: geometrical parameters synthesis [16, 22], position and kinematic analysis [7, 11, 10, 8], strength analysis [11, 8], dynamical modeling [4,5,10,18], vibration analysis [3], control [1,14,19,29], parameters identification and validation [12,23].

Serious attention should be paid to the position and static force analysis of the excavator. These activities are very important not only in the preliminary stages of the design process, but also in the real exploitation conditions for evaluation of the machine technical capabilities. The position analysis of the backhoe excavating equipment (especially the working zone dimensions) is very important for the studying of its technical-economic parameters; also, it is used in the following-up static force analysis.

In the most cases of the real digging processes, the static component of the kinematic joint reactions prevails vastly over the dynamic one. By the reason of that, the working engineers use the calculated or measured maximal static forces in the joints with the suitable safety factor for the mechanical system strength calculations [20].

Some approaches are possible for position and static force analysis of this type of equipment. Widely used well known manual [13] and semiautomated [6] graphical and graph-analytic methods are expensive, especially for studying the joints reactions in few different geometrical configurations of the excavating equipment in the working zone. The analytical approach to the problem [8,17] leads to composition and solution of the big and complex systems of linear and nonlinear algebraic equations. The treatment of the statics as a particular case of the dynamics [15] is also expensive and is accompanied by computational difficulties. The simulation modeling via unspecialized software products [24,25,27,28] imposes some essential constraints to the models, performed activities and results.

There are few computer programs, implemented in algorithmic programming languages, which partially automate the position and static force analysis [11, 16], but they are practically inaccessible for wide audience.

On the basis of the performed literature study and the practical need, the objective of the present study is defined as: to propose and develop algorithms for position and static force analysis of a hydraulic excavator kinematic chain as well as to realize these algorithms in a web based environment.

II. THE ALGORITHMS

II.1 ALGORITHM FOR POSITION ANALYSIS OF THE MECHANICAL SYSTEM

In the present study transformation matrices are used for determination of the position of any point from the kinematic chain [2, 7, 10]. Such an approach is well suited for computer implementation.

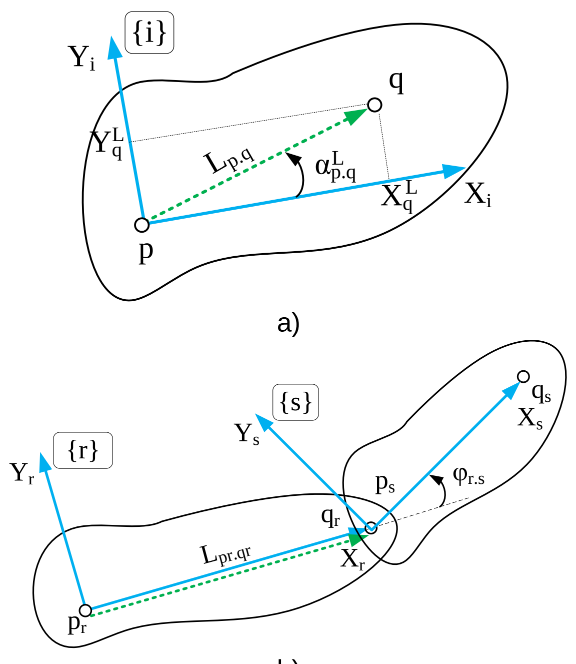
The kinematic chain of the backhoe equipment is a combination of open and closed loop contours. It consists of 10 rigid bodies which are interconnected by 14 joints. Each body is denoted by consecutive number *i* in the kinematic chain, and each joint by *n*, where *i=0,1,…,r,…,s,…,9*, *n=1,2,…,p,…,q,…,14* (see fig.3). The fixed link (ground) has a number *i=0*, the base machine has a number 1. There is a fixed cartesian coordinate system {0}, attached to the point 1 with horizontal and vertical axes (fig.2). To each body is attached local Cartesian coordinate system {i}. The position of an arbitrary chosen point *q* from a body in its local coordinate system, attached at the point *p*, is denoted by vector $\{V_{p.q}^L\}$ (see fig.2a):

$$\{V_{p.q}^L\} = \{X_q^L \;\; Y_q^L \;\; 1\}^T \qquad (1)$$

Cartesian coordinates of the point *q*, respectively X_q^L and Y_q^L, are determined by parameters $L_{p.q}$ and $\alpha_{p.q}^L$:

$$X_q^L = L_{p.q}\cos\alpha_{p.q}^L, \quad Y_q^L = L_{p.q}\sin\alpha_{p.q}^L \qquad (2)$$

With $L_{p.q}$ is denoted the distance between points *p* and *q*, and with $\alpha_{p.q}^L$ - angle between the line $\overline{pq}$ and X_i axis of the local coordinate system.



a) b)

Fig.2 a) Position and orientation of the local coordinate system; b) Parameters of the transformation matrix

For description of the relative position of two connected by joint bodies, which form an open kinematic chain, following transformation matrices are used (see fig.2b):

$$[T_i^{i-1}] = \begin{bmatrix} \cos\phi_{r.s} & -\sin\phi_{r.s} & L_{pr.qr} \\ \sin\phi_{r.s} & \cos\phi_{r.s} & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

where $\phi_{r.s}$ is the angle between links *r* and *s*.

At the fig.3 is shown the kinematic chain of the mechanical system under consideration, the joints, the points of interest and the position and orientation of the attached to the bodies local coordinate systems.

For the operating equipment under consideration (see fig.3), the open kinematic chain is formed by bodies 0 (terrain),1 (base machine), 2 (boom), 5 (stick), 9 (bucket). Position and orientation of the hydraulic cylinders and four-bar mechanism depends on them.

Transformation matrices between the local coordinate systems of the bodies 0,1,2,5,9 are:

$$[T_1^0] = \begin{bmatrix} \cos\phi_{1.2} & -\sin\phi_{1.2} & 0 \\ \sin\phi_{1.2} & \cos\phi_{1.2} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$[T_5^2] = \begin{bmatrix} \cos\phi_{8.13} & -\sin\phi_{8.13} & L_{4.8} \\ \sin\phi_{8.13} & \cos\phi_{8.13} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$[T_9^5] = \begin{bmatrix} \cos\phi_{13.15} & -\sin\phi_{13.15} & L_{8.13} \\ \sin\phi_{13.15} & \cos\phi_{13.15} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$\phi_{1.2} = \alpha_{1.2}^L + \alpha_{ter} \qquad (4)$$

The joint coordinates and the body character points at the fixed coordinate system {0} are determined by the equation:

$$\{V_{p.q}^0\} = [T_i^0]\{V_{p.q}^L\} = \{X_q \;\; Y_q \;\; 1\}^T \qquad (5)$$

For considered mechanical system the following relations are valid:

-for body 1:

$$\{V_{1.2}^0\} = [T_1^0]\{V_{1.2}^L\}, \; \{V_{1.3}^0\} = [T_1^0]\{V_{1.3}^L\},$$
$$\{V_{1.4}^0\} = [T_1^0]\{V_{1.4}^L\}, \; \{V_{1.G_1}^0\} = [T_1^0]\{V_{1.G_1}^L\} \qquad (6)$$

-for body 2:

$$\{V_{4.8}^0\} = [T_1^0][T_2^1]\{V_{4.8}^L\}, \{V_{4.6}^0\} = [T_1^0][T_2^1]\{V_{4.6}^L\},$$
$$\{V_{4.5}^0\} = [T_1^0][T_2^1]\{V_{4.5}^L\}, \; \{V_{4.G_2}^0\} = [T_1^0][T_2^1]\{V_{4.G_2}^L\} \qquad (7)$$

-for body 5:

$$\{V_{8.7}^0\} = [T_1^0][T_2^1][T_5^2]\{V_{8.7}^L\}, \{V_{8.9}^0\} = [T_1^0][T_2^1][T_5^2]\{V_{8.9}^L\}$$
$$\{V_{8.12}^0\} = [T_1^0][T_2^1][T_5^2]\{V_{8.12}^L\},$$
$$\{V_{8.13}^0\} = [T_1^0][T_2^1][T_5^2]\{V_{8.13}^L\},$$
$$\{V_{8.G_5}^0\} = [T_1^0][T_2^1][T_5^2]\{V_{8.G_5}^L\} \qquad (8)$$

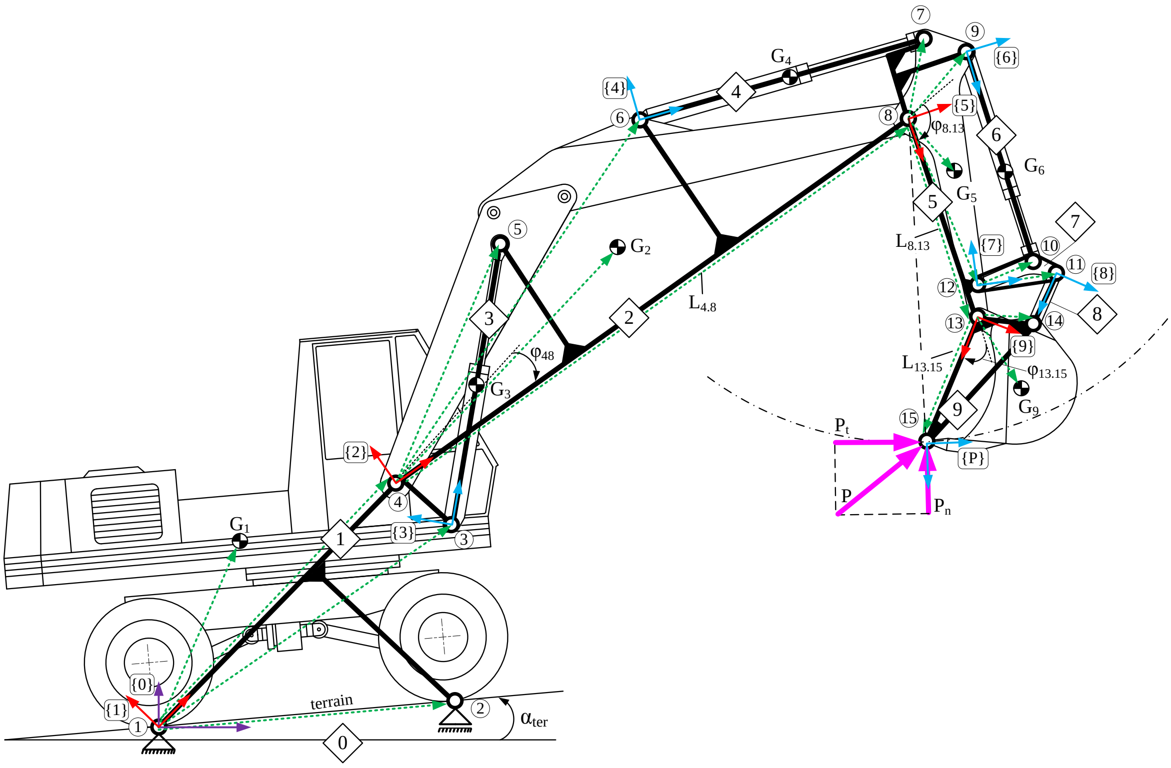


Fig.3 Kinematic scheme of the mechanical system

- for body 9:

$$\{V^{0}_{13.14}\}=[T^{0}_{1}][T^{1}_{2}][T^{2}_{5}][T^{5}_{9}]\{V^{L}_{13.14}\}\,,$$

$$\{V^{0}_{13.15}\}=[T^{0}_{1}][T^{1}_{2}][T^{2}_{5}][T^{5}_{9}]\{V^{L}_{13.15}\}\,,$$

$$\{V^{0}_{13.G_9}\}=[T^{0}_{1}][T^{1}_{2}][T^{2}_{5}][T^{5}_{9}]\{V^{L}_{13.G_9}\} \qquad (9)$$

The inclination angle of each body towards axis X_0 is determined via the coordinates of two points, which belongs to the body, in the fixed coordinate system {0} by standard function of two arguments atan2(y,x), through which the angle can be calculated in the interval (-π,+ π]. For the studied mechanical system can be written:

$$\phi_{B1}=\phi_{1.2}\,,\ \phi_{B2}=\text{atan2}(Y_8-Y_4,X_8-X_4)\,,$$

$$\phi_{B3}=\text{atan2}(Y_5-Y_3,X_5-X_3)\,,$$

$$\phi_{B4}=\text{atan2}(Y_7-Y_6,X_7-X_6)\,,$$

$$\phi_{B5}=\text{atan2}(Y_{13}-Y_8,X_{13}-X_8)\,,$$

$$\phi_{B6}=\text{atan2}(Y_{10}-Y_9,X_{10}-X_9)\,,$$

$$\phi_{B7}=\text{atan2}(Y_{11}-Y_{12},X_{11}-X_{12})\,,$$

$$\phi_{B8}=\text{atan2}(Y_{14}-Y_{11},X_{14}-X_{11})\,,$$

$$\phi_{B9}=\text{atan2}(Y_{15}-Y_{13},X_{15}-X_{13}) \qquad (10)$$

The length of the hydraulic cylinders depends on the current inclination angle of the corresponding body, which forms an open kinematic chain and is calculated by the following equation:

$$L_{Bi}=\sqrt{(X_{pi}-X_{qi})^2-(Y_{pi}-Y_{qi})^2} \qquad (11)$$

According to (11) the lengths of the hydraulic cylinders 3,4 and 6 are:

$$L_{B3}=\sqrt{(X_5-X_3)^2-(Y_5-Y_3)^2}\,,$$

$$L_{B4}=\sqrt{(X_7-X_6)^2-(Y_7-Y_6)^2}\,,$$

$$L_{B6}=\sqrt{(X_{10}-X_9)^2-(Y_{10}-Y_9)^2} \qquad (12)$$

The coordinates of hydraulic cylinders gravity centers in the fixed coordinate system {0} are functions of the position and orientation of the open kinematic chain bodies and can be calculated by equations (13). It is presumed, that the gravity centers are situated in the middle of the hydraulic cylinders.

$$\begin{Bmatrix}X_{G3}\\Y_{G3}\end{Bmatrix}=\begin{Bmatrix}X_3\\Y_3\end{Bmatrix}+\left[R^0_3\right]\begin{Bmatrix}\frac{1}{2}L_{B3}\\0\end{Bmatrix},$$

$$\begin{Bmatrix}X_{G4}\\Y_{G4}\end{Bmatrix}=\begin{Bmatrix}X_6\\Y_6\end{Bmatrix}+\left[R^0_4\right]\begin{Bmatrix}\frac{1}{2}L_{B4}\\0\end{Bmatrix},$$

$$\begin{Bmatrix}X_{G6}\\Y_{G6}\end{Bmatrix}=\begin{Bmatrix}X_9\\Y_9\end{Bmatrix}+\left[R^0_6\right]\begin{Bmatrix}\frac{1}{2}L_{B6}\\0\end{Bmatrix} \qquad (13)$$

where $[R^0_3]$, $[R^0_4]$ and $[R^0_6]$ are the rotation matrices of the hydraulic cylinders local coordinate systems in relation to fixed coordinate system {0}:

$$[R^0_3]=\begin{bmatrix}\cos\phi_{B3} & -\sin\phi_{B3}\\ \sin\phi_{B3} & \cos\phi_{B3}\end{bmatrix},[R^0_4]=\begin{bmatrix}\cos\phi_{B4} & -\sin\phi_{B4}\\ \sin\phi_{B4} & \cos\phi_{B4}\end{bmatrix},$$

$$[R^0_6]=\begin{bmatrix}\cos\phi_{B6} & -\sin\phi_{B6}\\ \sin\phi_{B6} & \cos\phi_{B6}\end{bmatrix} \qquad (14)$$

When the lengths of the bodies and the coordinates of the joints 12 and 14 are known, the current geometric location of the four-bar mechanism is defined by the coordinates X_{11} and Y_{11} of the joint 11 in the fixed coordinate system {0}. These coordinates can be calculated from the following system of nonlinear algebraic equations:

$$\begin{Vmatrix} (X_{14}-X_{11})^2+(Y_{14}-Y_{11})^2=L_{14.11}^2 \\ (X_{12}-X_{11})^2+(Y_{12}-Y_{11})^2=L_{12.11}^2 \end{Vmatrix} \quad (15)$$

Thus, the relations from (5) to (15) define the coordinates of all bodies in the fixed coordinate system, also other geometric parameters – lengths of the hydraulic cylinders and inclination angles of the bodies.

The performed position analysis is used for definition of the current geometric configuration of the operating equipment and is used in the following-up static force analysis.

III.2. Algorithm for static force analysis of the mechanical system

The main goal of the performed static force analysis is to determine the joint reactions and the reactions between the wheels and the terrain as a function of the digging force, due to working environment.

In order to apply the conditions for static equilibrium of the bodies it is necessary that the number of the degrees of freedom *h* of the mechanical system has to be equal to zero. The Chebishev's formula (16), applied to the system under consideration has the form (17).

$$h=3n-2p_5-p_4=0 \quad (16)$$

$$h=(3)9-(2)13-1=0 \quad (17)$$

where n is the number of links, p_5 and p_4 are the numbers of kinematic joints from fifth and fourth class.

There is assumed, that the digging force is concentrated at the bucket teeth [21] and is characterized by its value and direction. The direction of the digging force is considered as conservative in relation to the digging trajectory. The force makes approximately a constant angle γ with the trajectory tangential line (fig.4).

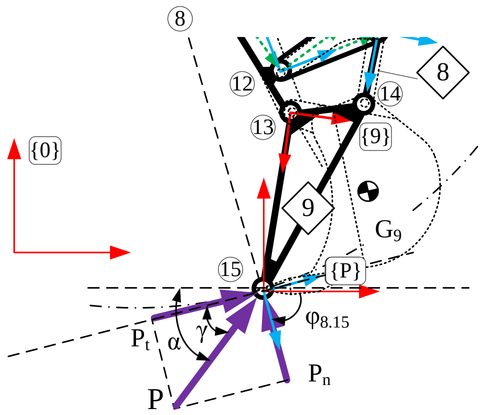


Fig. 4 Digging force and its components

The digging force is characterized by its value and direction. The normal P_n and tangential P_t components of the digging force P are defined in the coordinate system {P}. This coordinate system is attached to the tip of the bucket tooth, its x and y axes are normal and tangential respectively to the trajectory (fig.4). The following relations are valid:

$$\gamma=\operatorname{atan}(P_n/P_t)=\operatorname{atan}(f),$$
$$\alpha=\operatorname{atan}(P_x/P_y)=\operatorname{atan}(k) \quad (18)$$

$$k=\frac{\cos\varphi_{8.15}f+\sin\varphi_{8.15}}{\sin\varphi_{8.15}f-\cos\varphi_{8.15}},$$
$$f=\frac{\cos\varphi_{8.15}k+\sin\varphi_{8.15}}{\sin\varphi_{8.15}k-\cos\varphi_{8.15}} \quad (19)$$

$$\begin{Bmatrix} P_x \\ P_y \end{Bmatrix}=[R_P^0]\begin{Bmatrix} -P_n \\ P_t \end{Bmatrix} \quad (20)$$

$$[R_P^0]=\begin{bmatrix} \cos\varphi_{8.15} & -\sin\varphi_{8.15} \\ \sin\varphi_{8.15} & \cos\varphi_{8.15} \end{bmatrix} \quad (21)$$

$$P_t=\sqrt{\frac{P^2}{1+f^2}} \quad (22)$$

The conditions for static equilibrium of the bodies are obtained by removing the joints and application of internal and external forces on the bodies (fig.5).

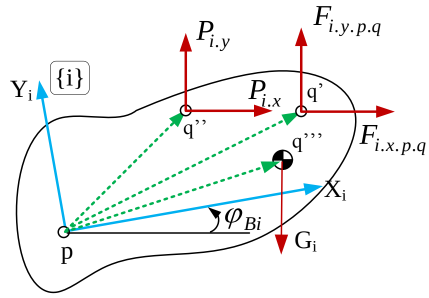


Fig.5 Free body diagram of the body *i* and applied to it internal and external forces

External forces applied to the mechanical system are: 1) the gravity forces $G_1 \div G_9$, which acts at the gravity center in vertical direction; 2) the digging force P. The friction forces and moments in the hydraulic cylinders and joints are neglected.

The necessary and sufficient conditions for equilibrium of body *i* with applied planar forces are:

$$\sum\begin{Bmatrix} \{F_{i.p.q}\} \\ M_{F.i.p} \end{Bmatrix}+\sum\begin{Bmatrix} \{P_{i.}\} \\ M_{P.i.p} \end{Bmatrix}+\begin{Bmatrix} \{G_i\} \\ M_{G.i.p} \end{Bmatrix}=0 \quad (23)$$

where $\{F_{i.p.q}\}=\{F_{i.x.p.q}\quad F_{i.y.p.q}\}^T$, $\{P_i\}=\{P_{i.x}\quad P_{i.y}\}^T$ and $\{G_i\}=\{0\quad -G_{i.y}\}^T$ are the vectors of internal forces $F_{i.p.q}$, external forces P_i and gravity forces G_i in the fixed coordinate system; $M_{F.i.p}=\{F_{i.p.q}\}^T[A_i]\{V_{p.q}^L\}$ - the moments of the internal forces; $M_{P.i.p}=\{P_i\}^T[A_i]\{V_{p.q}^L\}$ - the moments of the external forces; $M_{G.i.p}=\{G_i\}^T[A_i]\{V_{p.q}^L\}$ - the moments of the gravity forces in the local coordinate systems. All moments are computed in relation to the point of attachment of the body local coordinate system.

The matrix $[A_i]$ has the following form:

$$[A_i]=\begin{bmatrix} -\sin\phi_{Bi} & -\cos\phi_{Bi} \\ \cos\phi_{Bi} & -\sin\phi_{Bi} \end{bmatrix} \quad (24)$$

The conditions of static equilibrium are composed by application of equation (23) to each body. The solution of the obtained system of 27 linear algebraic equations gives the static reactions in all joints – Fig.6.

For determination of the normal and tangential to the terrain forces between the wheels and the terrain, received horizontal and vertical reactions at joints 1 and 2 are additionally projected by proper rotation matrix in the coordinate system, which *x* and *y* axes are along and perpendicular respectively to the terrain.

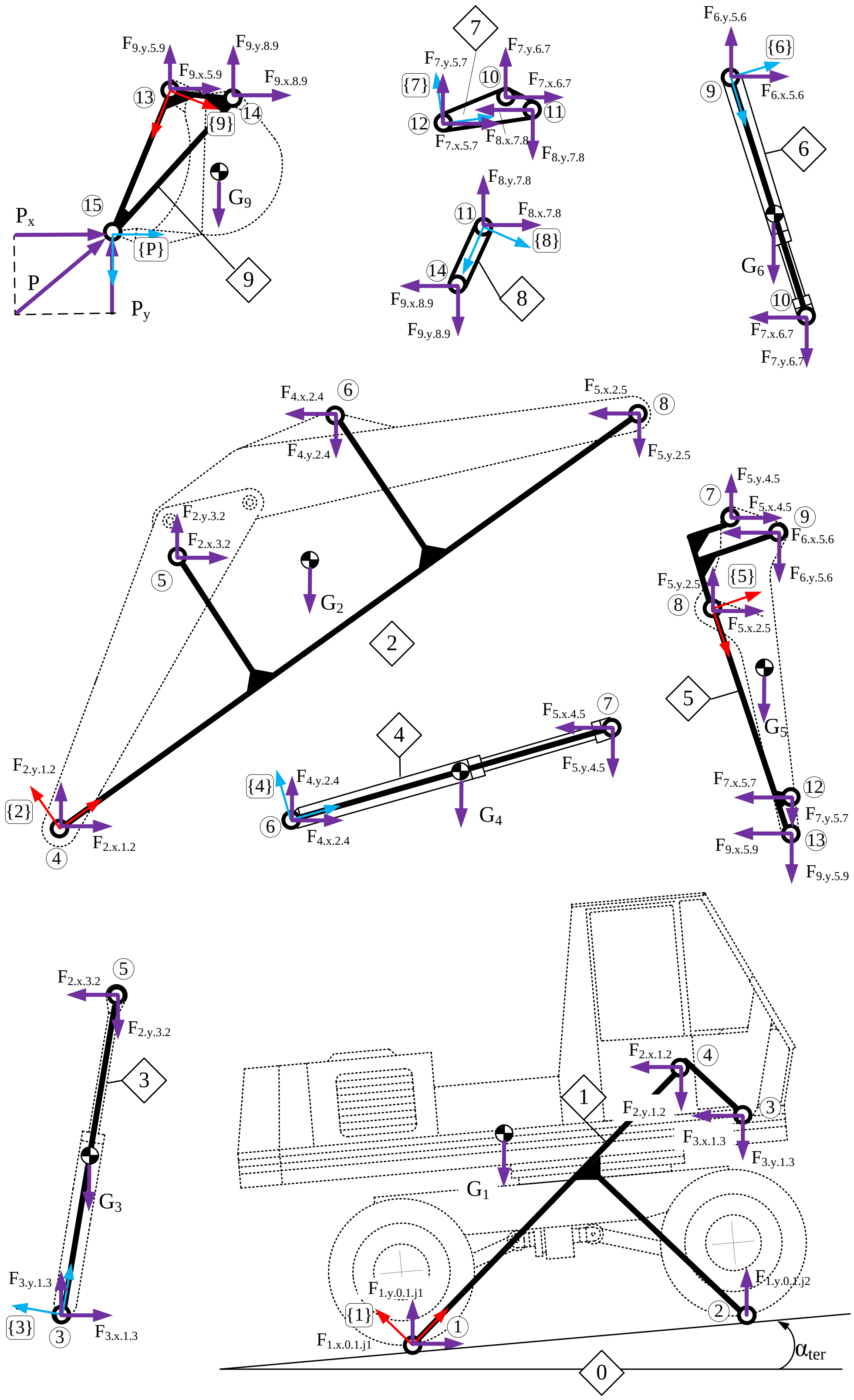


Fig.6. Free body diagrams of the links

III. WEB BASED IMPLEMENTATION OF THE DEVELOPED ALGORITHMS

The suggested and developed algorithms for position and static force analysis are implemented in the web based environment. Our choice is to develop Web based tool for design and analysis, because of the following of its obvious advantages [4, 26]: 1) everyone is connected everywhere and at any time; 2) there is assured speedy communication and large quantity of information resources; 3) there is possibility to use the tool on mobile devices which allow performing of the simulations in field conditions; 4) there are available powerful program tools for the implementation of the developed engineering and visualization modules in a Web based environment; 5) used algorithms are available for preview from the user and can be further developed.

In our case the Web based simulation tool is implemented consisting of the following program modules:

- Input module which provides geometrical and force parameters of the excavator. The program input data are the geometric parameters of the links, the angles of rotations of the links, which form the open kinematic chain (boom, stick and bucket), also the inclination angle of the terrain α_{ter}, value of the parameter *f* and the value of the digging force *P*.
- Module for computation of links rotations, joints positions and joints static forces. There are used libraries for solution of the systems of linear and nonlinear algebraic equations, matrix handling and tools for processing and visualizations of the results. The angles of rotation of the boom (body 2) $\varphi_{4.8}$ and the stick (link 5) $\varphi_{8.13}$ are discretized by step *k* and *m* respectively and they values are changed by two sliders. The developed algorithms are applied to every particular geometrical configuration of the backhoe equipment, i.e. *k*m* times. Angle of rotation of the bucket (body 9) $\varphi_{13.15}$ also can be changed, but in the calculations it is assumed to be constant.
- Module for visualization of results in graphical and numerical form. Output of the program is a set of parameters, based on the performed calculations – dimensions and the form of the working zone, current geometrical configuration of the excavating equipment, static forces graphs as a function of the angles of rotations and maximal values of the reactions at the joints. The output results can be easy modified for particular needs.

The verification of the program is performed by the comparison of the results with the results from the classical graph-analytic approach for joint forces determination.

An experimental Web based application, has been developed and tested. The work with the application starts by the preparation of the XML model. On the user side is prepared an XML model of mechanical assembly (the model contains information about the geometrical description of the linkage, parameters of its movement and some instructions about the graphical presentation – Fig.7). XML model is sent and stored on the server and PHP file generates related to the concrete task Web page with graphical presentation of the mechanical system.

At the fig.8 are shown the web visualization of a geometric configuration of and working zone of the operating equipment and 3D graphs for joints forces for the shown particular geometrical configuration of the equipment. In the current numerical example are used geometrical parameters of the hydraulic excavator BEN 195 and the following values of the angles of rotation: $\varphi_{4.8}=0\div120^{o}$, $\varphi_{8.13}=20\div140^{o}$, $\varphi_{13.15}=20^{o}$.

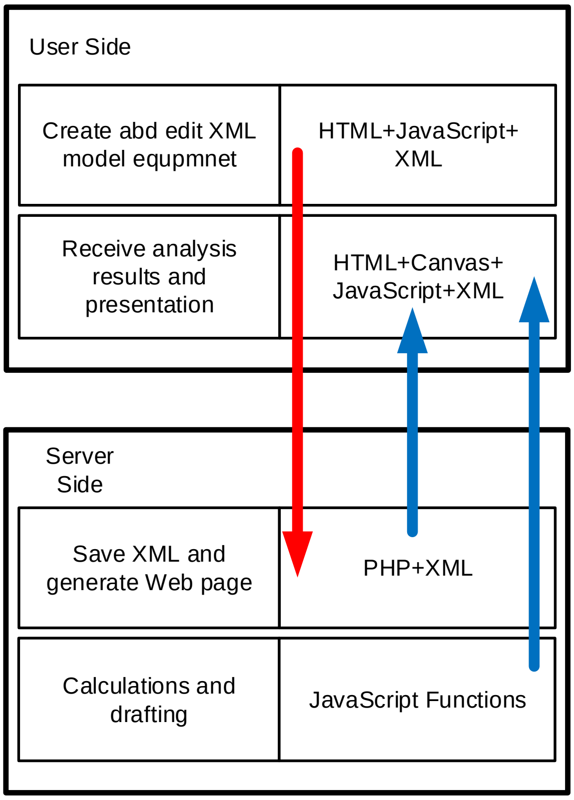


Fig. 7 Technologies used for development of the web experimental application

IV. CONCLUSIONS

The web based environment discussed here facilitates the time consuming process of design and analysis. The proposed approach and technical means provide an opportunity to increase the quality of the position and static force analysis of the hydraulic excavator. Development and implementation of these tools will inevitably lead to easing the labor of persons engaged in these activities, and to achieve positive economic impact in terms of resources - humans, energy and time. A web based environment for design, analysis and visualization is implemented, which uses the developed algorithms for position and static force analysis.

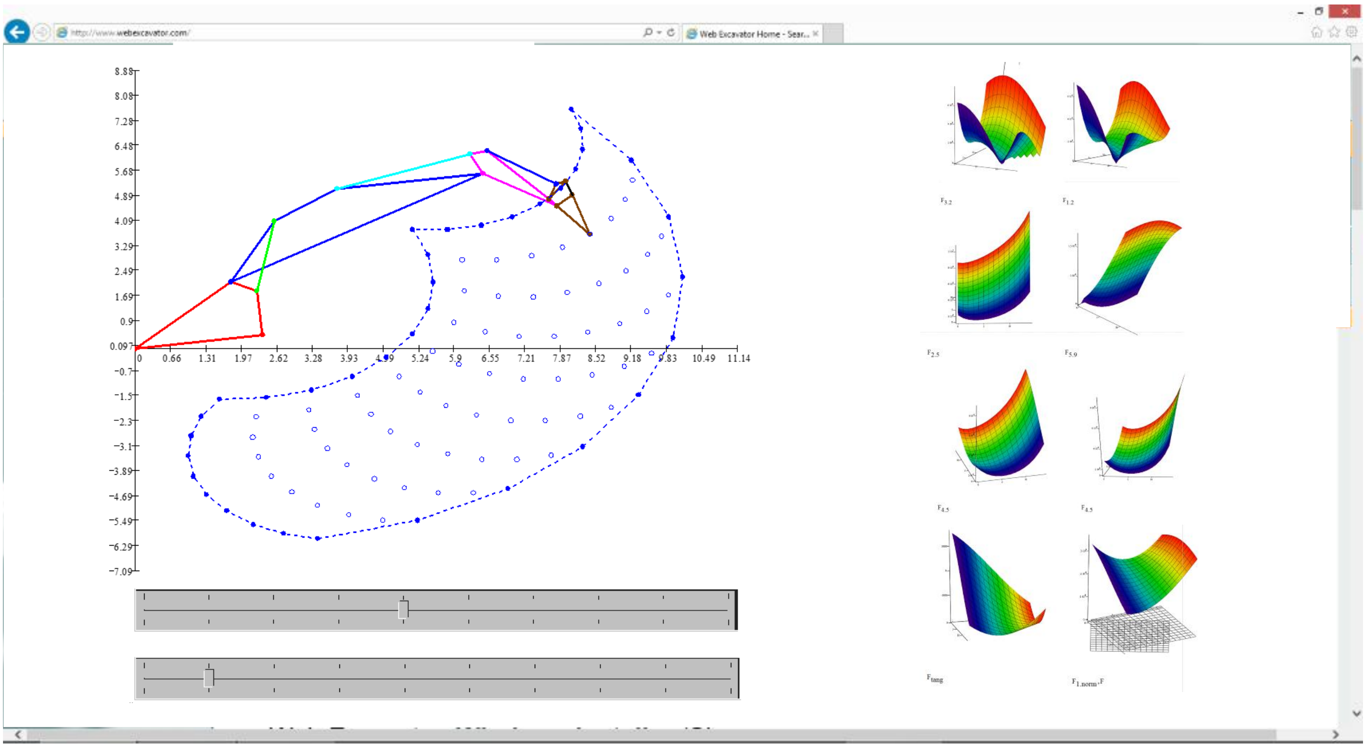


Fig.8 Web based environment for visualization of the geometric configuration of the operating equipment, the working zone and the graphs joint forces

REFERENCES

[1] Budny, E., Chłosta, M., Gutkowski, W., Optimal control of an excavator bucket positioning. International Symposium on Automation and Robotics in Construction, 19th (ISARC). Proceedings. National Institute of Standards and Technology, Gaithersburg, Maryland. September 23-25, 2002, pp.481-488.

[2] Craig, J., Introduction to robotics. Mechanics and control. Addison-Wesley publishing company 1989.

[3] Ding, G., Qian, Z., Feng, P., Pan, S., Active Vibration Control of Excavator Working Equipment with ADAMS. North American ADAMS User Conference, Orlando, FL 2002

[4] Frimpong, S., Yafei, H., Inyang, H., Dynamic Modeling of Hydraulic Shovel Excavators for Geomaterials. International Journal of Geomechanics, Jan.2008, Vol. 8 Issue 1, pp.20-29; DOI: 10.1061/(ASCE)1532-3641(2008)8:1(20).

[5] Janssen, B., Nievelstein, M., Multi-loop Linkage Dynamics via Geometric Methods: A Case Study on a RH200 Hydraulic Excavator, Internship report, Eindhoven University of Technology Department of Mechanical Engineering Dynamics and Control Group, 2005.

[6] Hlebosolov, I., Grafoanaliticheskie metodi rascheta mehanizmov s ispolzovaniem EVM. Journal of theory of mechanisms 2004, №2, Vol.2, pp.40-44, (in Russian).

[7] Hofstra, C., Hemmen, A., Miedema, S., Hulsteyn, J., Describing the position of backhoe dredges. Texas A&M 32nd Annual Dredging Seminar. Warwick, Rhode Island, June 25-28, 2000.

[8] Hsin-Sheng, L., Shinn-Liang, C., Kuo-Huang, L., A study of the design, manufacture and remote control of a pneumatic excavator. International Journal of Mechanical Engineering Education. Volume 32(2004), Issue 4, pp. 345-362.

[9] Koivo, A.,. Kinematics of excavators (backhoes) for transferring surface material. Journal of Aerospace Eng., 7(1), pp.17–32., 1994.

[10] Koivo, A. Thoma, M., Kocaog-lan, E., Andrade-Cetto, J., Modeling and control of excavator dynamics during digging operation. Journal of Aerospace Eng., 9(1), pp.10 –18. 1996.

[11] Malinovskii, Y., Zareckii, L., Berengard, Y., Gajcgori, M., Goldin, Y., Chastuhin L., Raschet I proektirovanie straoitelnih I dorozhnih mashin na EVM. Moskva, Mashinostroenie 1980 (in Russian).

[12] Malaguti, F., Zaghi, S., Force Sensor by Driving Hydraulic Cylinders: Identification of Inertial Parameters and Tests. International Symposium on Automation and Robotics in Construction, 19th (ISARC). Proceedings. National Institute of Standards and Technology, Gaithersburg, Maryland. September 23-25, 431-436 pp., 2002.

[13] Minchev, N., Zhivkov, V., Enchev, K., Stoianov, P., Teoria na mashinite i mehanizmite. Sofia, Tehnika 1991 (In Bulgarian).

[14] Nguyen, H. Robust low level control of robotic excavation, Ph.d thesis, Australian Centre for Field Robotics,The University of Sydney 2000.

[15] Shabana, A., Computational dynamics. Wiley-Interscience 2001.

[16] Tsustsekov, E., Danchev, D, Panov,V., Algoritam i programa za proektirane na rabotno saorazhenie na hidravlichen bager. Proceedings of

the "Lenin" higher institute of mechanical and electrical engineering – Sofia,, volume 39, book 1, pp.47-59, 1985. (In Bulgarian)

[17] Uicker, J., Pennock, G., Shigley, J., Theory of Machines and Mechanisms. Oxford University Press, New York 2003.

[18] Vaha, P., Shibniewski, M., Dynamic model of excavator. Journal of. Aerospace Engineering, 6 (2), pp.148–166., 1990.

[19] Velzen, R., Automatisering van de positie en stand van de bucket van een backhoedredger, Afstudeerverslag A-863 vakgroep Meet- en regeltechniek, Faculteit Werktuigbouw en Maritieme Techniek, Delft 1999.

[20] Volkov, D., Krikun, V., Totolin, P., Gaevskaia, K., Nikulin, P., Mashini dlia zemlianih rabot. Moskva, Mashinostroenie 1992. (In Russian).

[21] Zelenin, A., Balovnev, V., Kerov, I., Machines for moving the earth, Amerind Publishing, New Delhi, India 1985.

[22] Minin I. Trajectory of movements of characteristics points of the working body of hydraulic one-bucket excavator type O&KRH 200 C. Bulgarian journal for engineering design, issue 12, may 2012, ISSN 1313-7530. (In Bulgarian)

[23] Savov S. Experimental research of vibrational parameters of one cone inertial crusher (KID-300) Bulgarian journal for engineering design, issue 27, october 2015, ISSN 1313-7530. (In Bulgarian)

[24] [www.ansys.com]

[25] [www.solidworks.com]

[26] R. Mitrev, B. Tudjarov, N. Kubota, Web based solutions for mechanical engineering, Proc. of the conference IWACIII '2013, Shanghai, China, 18-21 October 2013, pp. GS2-9. 1-GS2-9. 6.

[27] Mitrev R., Gruychev R., Pobegailo P., CAD/CAE investigation of a large hydraulic mining excavator, Machine Design vol.3 (2011), no.1.

[28] Hristov V., Improvement of forwarding mechanism with multiple network links, International Journal of Open Problems in Computer Science and Math., Vol. 6, No. 3, September 2013 ISSN 1998-6262, pp. 74-81.

[29] Markov B. Control of the permanent magnet linear synchronous motor with fuzzy and PID regulators", Industrial engineering and environmental protection 2014.