Preliminary note

CAD/CAE INVESTIGATION OF A LARGE HYDRAULIC MINING EXCAVATOR

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Abstract: The present work is devoted to CAD/CAE investigation of the mechanical system of large mining excavator with Tripower system. The investigation is performed in Autodesk Inventor environment and its dynamical simulator. A 3D model of the excavator working equipment is developed and it is used for investigation of the geometrical, force, kinematical and dynamical parameters of the mechanical system. Also investigation of these parameters for an operating cycle of the excavator is performed.

Key words: CAD/CAE, excavator kinematics, dynamics, Tripower

1. INTRODUCTION

The excavators are popular multifunctional construction and mining machines. Excavator consists of traveling body, swing body and front digging manipulator, by which digging operations are performed. The digging manipulator consists of a number of moving elements, main of which are boom, stick and bucket, connected by rotational joints. These elements are powered by hydraulic cylinders, which are connected to the excavator links and working tools directly or through transmission mechanisms. Actuation of the elements is by extension and retraction of the hydraulic cylinders, commanded by the operator.

When mining operations are performed it is desirable to keep the constant inclination of the bucket along the path of digging and transportation of the material. Usually, because of the bucket is attached to the stick, its inclination depends on the inclination of the boom and stick. That’s why during the motion an additional correction of the bucket inclination by bucket cylinder is necessary to keep its preset inclination. Constant inclination of the bucket could be achieved by mechanical linkages or by hydraulics. There are few possibilities to design such types of linkages and the most advanced of them is the patented by O&K Tripower system.

The Tripower system was invented by a O&K engineer in 1989 to make working for the operator easier by actuation of only one cylinder for bucket crowd and lifting. Although the patent expired in 2000, Terex is still the only one manufacturer of excavators with Tripower system.

The kinematical scheme of the Tripower system is shown at Fig.1. The mechanism consists of 9 links (including ground) and has 3 degrees of freedom. Boom 1, stick 2 and bucket 3 are actuated by hydraulic cylinders 4, 5 and 6. The hydraulic cylinders 4 and 5 are not directly connected to the boom 1, but through a triangular rotatable element 8. This element is connected to a superstructure via a rod with constant length 7. The preset inclination of the bucket is achieved in two cases: 1) When the cylinder 4 extends (cylinder 5 also could extend or could be blocked), it lifts the boom 1 and element 8 rotates clockwise. Because of cylinder 6 is blocked, it acts as a rod with constant length. Element 8 pulls the bucket 3 and it rotates counterclockwise, keeping its preset inclination; 2) Cylinder 5 extends and cylinders 6 and 4 are blocked. In this case the bucket also keeps the preset inclination.

Modeling and investigation of the excavator, particularly kinematics and dynamics of the digging manipulator is a challenging task and a topic of increasing importance for designers, due to presence of potential for reducing prototyping costs and providing the better understanding of the mechanical system behavior.

In the present paper, an investigation of geometrical, force, kinematical and dynamical parameters of a large hydraulic excavator with Tripower system is presented.

2. LITERATURE SURVEY

There is a massive collection of papers which considers the investigation of mechanical system parameters, especially kinematics and dynamics of excavators work attachment.

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Some authors have derived the kinematic relationships that relate joint angles of a backhoe to the location and orientation of the bucket tip [8]. Other authors [5, 11] have developed a kinematic model for an excavator. The model takes as input the forces generated by the hydraulic actuators and provides as output the position of the bucket. The authors of [16] have proposed a Lagrangian formulation of wheel loader dynamics where the machine is represented as a three link manipulator. Another model based on the Newton-Euler method is developed in [18]. Other researchers [14] also have used a similar formulation to model excavators modified for forestry applications. Dynamic modeling of mining machinery excavators is presented in [4]. Dynamic models of the hydraulic shovel excavator have derived for its boom, stick and bucket, and are analyzed as free body diagrams using the iterative Newton-Euler method. Mathematical model for a hydraulic actuator with pump-controlled system is presented in [1] and the motion of the boom of hydraulic excavator has modeled and simulated as an example. The author of [21] has used the Lagrange equations for the dynamics of the hydraulic excavator.

The modeling of the excavators and similar machines as multibody systems is not widely considered in the published literature. The paper [10] describes a geometric method for formulation of constrained multiloop linkage dynamics which is applied to large mining excavator with Tripower system. Domain decomposition method with iteration is proposed and applied to dynamic simulation of hydraulic excavator in [9]. A method to obtain a low order dynamic model for multilink flexible hydraulic cranes is presented in [13]. A mathematical model of large-scale mobile construction manipulator is represented by a coupled system of nonlinear ordinary differential equations, formulated in minimal coordinates is developed in [7]. Based on Kane dynamic equations, the method of establishing analytical dynamic model for 6 DOF industrial robotic manipulators containing closed chain for spraying is put forward, and the dynamic equations in explicit form are derived in [12]. Reference [19] investigates the modeling and control of a full-scale unmanned excavator vehicle. The developed model takes into account the kinematics and dynamics of the mobile platform (vehicle) and the excavation arm. The authors of paper [20] have adopted the multibody approach and DAE formulation of excavator and front loader dynamics.

3. THEORETICAL APPROACH FOR DYNAMICAL INVESTIGATION OF THE EXCAVATOR

Mechanisms can be generally categorized into open-loop mechanisms and closed-loop mechanisms. The difference is that the joint degrees of freedom (DOF) in open loop mechanisms are independent of one another whereas in closed-loop mechanisms they are not independent. Extensive information on open- and closed-loop mechanisms is available from standard engineering books. The linkage of the Tripower system could be presented as multibody mechanical model containing links, which forms open and closed kinematic loops. The dynamic simulation of the closed-loop system is more difficult then the open-loop system. In comparison with open-loop systems, closed-loop systems tend to possess relatively few degrees of freedom compared to the number of connected bodies. Kinematic loops introduce two difficulties: 1) there is no longer one-to-one correspondence between the joint variables and the motion freedoms of the system due to the loop closure equations; 2) to define the configuration of the system unambiguously more number of coordinates than the degrees of freedom is needed. A number of methods are available to formulate dynamics of multibody system, including the iterative Newton-Euler dynamic formulation, the Lagrangian formulation, Kane’s method, and others. Of course, all methods have benefits and drawbacks. Suitable for modeling of the considered mechanical system are well established in the analytical mechanics Lagrange equations of the first kind. They are used for deriving the equations of motion of the multibody system components:

\[
\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} + \sum_{j=1}^{m} \lambda_j \frac{\partial \phi_j}{\partial q_i} = Q_i \quad i = 1, 2, ..., n
\]

where \( L = T - U \) is the Lagrangian function; \( T \) is the kinetic energy of the system; \( U \) is the potential energy of the system; \( q_i, i=1,2,..,n \) are set of \( n \) dependent coordinates; \( \phi_j, j=1,2,..,m \) set of independent constraint equations; \( \lambda_i \) – Lagrange multipliers.

Equation (1) represents \( n \) equations with \((n+m)\) unknowns. In order to have a sufficient number of equations, it is necessary to supply \( m \) more equations. The obvious choice is to use the algebraic constraints equations (2) which along with (1) constitute a set of differential algebraic equations (DAE’s) of index three:

\[
\phi_j = 0 \quad j = 1, 2, ..., m
\]

Thus, the interconnection oriented modeling describes the dynamic behavior of the single body and the coupling of the subsystems by algebraic equations. This approach leads to a large system of loosely coupled equations that can be solved for the coordinates and Lagrange multipliers. The vector of Lagrange multipliers can be used to determine the generalized reaction forces. Taking into account Lagrange equations (1), expressions for kinetic and potential energies of the bodies, constraint equations and expressions for generalized forces we can generate equations of motion of the multibody system. The considered linkage consists of 11 bodies (if hydraulic cylinders are considered as consisting of two bodies) and
12 rotational and 3 translational kinematical pairs. The system of equations which describes the motion of multibody system consist of 33 differential equations of second order and 30 algebraic equations. Numerical solution of such large DAE system is difficult because of computational and numerical problems. More rational way for modeling of the considered system is to use a dedicated software.

4. CAD/CAE APPROACH FOR DYNAMICAL SIMULATION OF THE EXCAVATOR

An easy applied and widely used in engineering practice approach for simulation of the excavator as a multibody system is a modeling by way of general purpose mechanical dynamics software [3,15,17]. In the present work, Autodesk Inventor package and its dynamic simulator are used for modeling and simulation. A 3D CAD model of real life machine Terex/O&K RH-120E is developed—see Fig.2. At the figure are also drawn working zone of the excavator and global axes, according which all quantities are computed.

There is provided one to one correspondence between geometrical, force, kinematical and mass-inertial properties of real life machine and CAD model. From the viewpoint of dynamical simulation the excavator mechanism is viewed as a set of rigid bodies interconnected to each other by joints that constrain, but not restrict, relative motion between any two bodies. Common joints used in excavator mechanism include revolution, prismatic and fixed (grounded) joint. The process of creating dynamic simulation study consists of 4 core steps: 1) creation of cad model of the system; 2) creation of joints between components that have relative motion between them; 3) creation of environmental conditions to simulate reality; 4) performance of simulation and assessment of results.

As a result of performed simulation tasks are received results from the investigation of some of the mechanical system parameters.

4.1. Bucket inclination

Properly designed linkage must ensure that the bucket will be kept to preset constant angle of inclination while digging and lifting the bucket with excavated material. This condition is achieved at the stage of mechanism synthesis through choice of suitable geometrical parameters of the elements and their connection to other elements.

For evaluation of the bucket inclination along the digging or transportation path, a series of simulations are performed. Bucket inclination is evaluated when the boom is lifted (motion down-up) by its hydraulic cylinder and all other cylinders are blocked. The received results are depicted at Fig.3.

There are shown relations between the stroke of the boom hydraulic cylinder and the bucket tilt for different combinations of relative situation of the working equipment elements. Obviously, in all cases the bucket inclination changes along the motion path. Several additional experiments show that this change is larger around the border of working space (up to 15°). When digging or transportation operations in this zone are performed, it is possible to spill the excavated material or change the digging process parameters, that’s why a manual correction of the bucket inclination from the operator is needed. In the zones around the center of the working space deviation from the preset inclination is much smaller (4°÷5°) which cannot cause the mentioned problems.

4.2. Potential digging force along the digging path

According to adopted terminology [2], the potential (in other words-possible) digging force is the tangential digging force on the bucket tooth top, which can be realized when digging is performed by hydraulic cylinders and the pressure in them is maximal. To determine this potential digging force along the digging path, two experiments are performed: 1) The boom is lifted by its cylinder and the value of the digging force is
determined for different values of the boom cylinder stroke; 2) The stick is lifted by its cylinder and the value of the digging force is determined for different values of the stick cylinder stroke. The execution of the mentioned experiments needs determination of such value of tangential digging force, which keeps in equilibrium the system along the digging path for known maximal value of force in the hydraulic cylinder (of the stick or the boom)— see Fig.4. The investigation is performed for different strokes of the corresponding cylinders: for the boom cylinder - 500mm., 1000mm., 1500mm., 2000mm.; for the stick cylinder- 600mm., 1500mm., 3000mm.

Fig.4. The scheme for determination of the unknown value of the potential digging force

Results (Fig.5) for the determined digging force are depicted as relation between the force and the relative height of the bucket over its lowest position.

One can observe that: 1) When the digging is performed by the motion of the boom, the potential digging force increases when the relative height increases and this increase is stronger around the upper part of the working zone (relative height>0.7); 2) When the digging is performed by the motion of the stick, the potential digging force could be accepted as constant along the digging path.

4.3. Velocity and acceleration of the cutting tooth top

Velocities and accelerations of the working equipment links influence some important machine parameters: technological and technical-economical parameters, inertial forces on the links and excavated material, parameters of the interaction between the control system and the operator etc. Kinematical parameters of the cutting tooth top are important primarily for velocity of the soil cutting, which influences the working resistance of the soil and also it determines the speed of cutting tooth wear. At the Fig.6 are shown results for the velocity and acceleration of the bucket tooth top, received for different constant velocities (50mm/s, 100mm/s, 150 mm/s, 200mm/s, 250mm/s) of the boom hydraulic cylinder (motion down-up). One can see that the linear increase of the velocity of the hydraulic cylinder (50 mm/s, 100 mm/s, 150 mm/s, 200 mm/s, 250 mm/s) leads to approximately uniform increase of the tooth velocity (240mm/s, 480mm/s, 720mm/s, 960mm/s, 1200mm/s – for relative height = 0). From the other side, the acceleration of the same point is nonlinear. Increase of the relative height ≈0.8 leads to small change of the small velocity and respectively small values of acceleration. After the pointed value of relative height velocity decreases sharply and acceleration increases. Values of the accelerations are small and the excited inertial forces are minimal.

4.4. Mechanical system parameters during the operating cycle

Simulation of the operating cycle allow us to investigate the change of the mechanical system parameters for a operating cycle, to determine their maximal values for a cycle and situation of the working equipment elements in this moment of time. Also we can determine the duration
of the operating cycle and minimize it by execution of concurrent motions of the different links which will lead to increase in excavator performance.

An approximate operating cycle with duration of 37s is simulated. The sequence of motions and their durations are shown at the Fig.7. Velocities of the hydraulic cylinders rods are 200mm/s. At the same picture are shown durations of different forces acting on the working equipment during the cycle - digging force 600kN, weight of material in the bucket 294kN and weights of all elements. One can see that after the bucket unloading (21-24s.) in backward motion the motions of the bucket, stick and boom are executed together. The theoretical calculated excavator performance for 15m³ bucket and 37s duration of cycle is 2910t/h which value is close to published by manufacturer value of 3000t/h in test conditions.

At Fig.8 we can observe the change of velocity of the cutting tooth top and its components during the considered operating cycle. Maximal value of the cutting tooth velocity is about 4400mm/s which value is achieved during the rotation of the working equipment around vertical Z axis (see Fig.2). At the period of backward motion (when the motions of bucket, stick and boom are performed together) the maximal velocity is about 2600 mm/s. In all other parts of the operating cycle the value of velocity is much smaller than pointed values.

At the Fig.9 are depicted results for acceleration of the peak point of the cutting tooth. Again, the maximal value of acceleration is observed during the rotation of working equipment around the vertical axis. This acceleration has a value approximately 1300 mm/s² and is caused from rotation of the working equipment around vertical axis (centrifugal acceleration). Such a big acceleration causes additional inertial load on the working equipment links, especially in the forward motion when the bucket is full.
The developed CAD model of the excavator can be used for investigation of the inverse kinematics and dynamics, especially for trajectory generations. The computed forces in the kinematical pairs together with the applied external forces can be used for FEM simulation of the mechanical system.

5. CONCLUSION

The used CAD/CAE approach for investigation of large mining excavator is suitable for performing geometrical, force, direct and inverse kinematical and dynamical analysis of the working equipment mechanical system. By simulation it is possible to investigate the change of parameters during operating cycle and optimize it duration. Although the used CAD/CAE system has no built-in tools for optimization of the mechanical system parameters, optimization could be performed by trial and error method.

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