# Dynamic Simulation of a Hydraulic Excavator to Determine the Joint Reaction Forces of Boom, Stick, Bucket, and Driving Forces of Hydraulic Cylinders

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## Abstract

*To optimize the dimensions of the boom, stick of the hydraulic excavator and select the suitable hydraulic bucket, stick, and boom cylinders, the designer must determine the joint reaction forces and driving forces. These forces always alter in an excavator's working cycle. They are conventionally calculated by mathematical method. This conventional method is complicated and challenging to determine the maximum reaction forces, which can break the stick and boom. This article builds a 3D model and simulates a working cycle of the hydraulic excavator to find the reaction force diagrams of boom and stick as well as driving forces of hydraulic cylinders by using computer software PTC Creo Parametric. Based on these results, the designer easily calculates the maximum tensions of the dimensions of boom and stick in a working cycle to optimize their dimensions as well as selects suitable hydraulic cylinders.*

**Keywords:** *dynamic simulation, excavator design, joint reaction forces, driving forces, maximum tension*

## 1. Introduction

In the first half of the 20th century, because of the strong development of the construction industry, open-pit mining, the first cable generation excavators were born and used widely for digging and loading. In the second half of this century, cable excavator was significantly replaced by a hydraulic excavator. Hydraulic excavators are commonly used in construction, mining, digging and forestry. During working, the excavator driver must pay his attention to digging material parameters, soil-machine interaction conditions. Various manufacturers in Germany, Japan, Italy, France and the United States began to utilize the computer software for designing excavators (Rusiński, E., Czmochowski, J., Moczko, P., Pietrusiak, D, 2017). Like other vehicles, the hydraulic excavator is also divided into several parts (see Fig. 1). To determine the forces on joints of boom and stick, the designer must define working loads of excavator. One of the studies on mini excavator is the single action hydraulic cylinder. The state of the stick against the load in the working environment is monitored by setting up a closed cycle system. This stick of this mini excavator is mathematically modelled and invented for static and dynamic movement (Salcudean, S.S, Tafazoli, S., Lawrence, P.D., Chau, I, 1997).

In order to design the excavator better, the forces between the soil and the machine must be calculated especially during digging (Patel, B. P., Prajapati, J.M, 2011). To reduce the cost of designing and manufacturing, the dimensions and weights of the boom and the stick must be minimized by establishing an optimization model (Korucu, S., Küçük, A. E., Samtaş, G, 2017). Therefore, the maximum tensions of boom and stick must specify in a working cycle of the excavator (Orlemann, E.C, 2003). To determine the reaction forces in a whole working cycle of stick and boom as well as driving forces of hydraulic cylinders, the designer must build an excavator model. Bucket, stick, and boom move during working, hence the reference coordinate system of excavator, the coordinate system of bucket, stick and boom are assigned in their centre of gravity. Based on loads of bucket, stick and boom, the mathematical equations are established to find the forces and reaction forces on joints of stick and boom (Bhaveshkumar P. Patel, J. M. Prajapati, 2014). Paten and Prajapati (Patel, B.P., Prajapati, J.M, 2012) used the mathematical method to calculate the static forces of the bucket, stick and boom.

The mathematical methods were used to develop an excavator's kinematics dynamics and establish the relationship between excavator parameters and the resistive forces from the material formation during the excavation process. By using SIMULATION-X Environment, the trajectory for the bucket tip, driving forces of the boom, stick and bucket cylinder during excavating are calculated and shown in different charts (Alaydi, Juma Yousuf, 2009).

The developed system of differential equations is used to perform a numerical experiment with the inertial and geometrical data for the excavator. The typical digging task simulation demonstrates the applicability of the dynamical model for the study of the excavator motion simulation by Matlab Simulink (Belma Babovic, Almir Osmanovic, Bahrudin Saric, 2017). Enhanced visualization of calculated results, the reaction forces will be plotted on a force/reaction diagram for a working cycle. It makes the designer easy to find out a position with the biggest total of reaction forces (Rosen Mitrev, Dragoslav Janošević, Dragan Marinković, 2017).

The recent developments of dynamic mechanism design broaden mechanism design to include a wide range of motion evaluation functions. When a movement of mechanism is analyzed, it can be observed and recorded the analysis or can be measured quantities such as positions, velocities, accelerations, forces, and graph the measurement. It offers information about creating and working with mechanism models with or without the application of external forces. Simulation lets

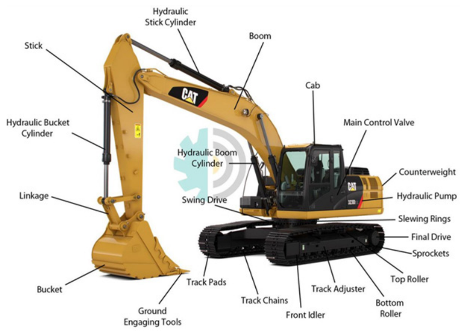



Fig. 1. Parts of hydraulic excavator

Rys. 1. Części koparki hydraulicznej

Tab. 1. Technical specifications of the excavator model (Kato works co., ltd)

Tab 1. Parametry techniczne modelu koparki

| Name | Values | Name | Values |
|---|---|---|---|
| Max. discharge flow of the pump | 470L/min | Max. discharge pressure of the pump | 32.4 MPa |
| Boom cylinders<br>Bore & Stroke | Two, double-acting<br>125mm×1,315mm | Stick cylinder<br>Bore & Stroke | One, double-acting<br>135mm×1,630mm |
| Bucket cylinder<br>Bore & Stroke | One, double-acting<br>120mm×1,090mm | Bucket mass<br>Bucket volume | 1,369 kg<br>800 $mm^3$ |
| Boom mass<br>Boom length | 2,937 kg<br>5,630 mm | Stick mass<br>Stick length | 1,153 kg<br>2,930 mm |
| Max. digging radius | 9,910 mm | Max. digging depth | 6,700 mm |
| Max. digging height | 9,760 mm | Max. vertical wall | 6,120 mm |
| Max. dumping height | 6,830 mm | Min. swing radius | 3,460 mm |

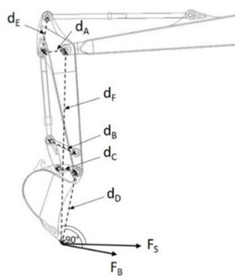



Fig. 2. Determination of breakout and digging forces (Patel et al., 2012)

Rys. 2. Wyznaczanie sił odspajania i kopania

the designer examine how his model will behave in the real world and reduces the need for costly prototype iterations. By using simulation, the 3D excavator model will be created that reflects the loads, materials, and boundary conditions. It also shows how to define and run a wide range of analyses and design studies, review results, and optimize the excavator model (Creo Parametric, 2020). For this reason, this research will design 3D-Cad model of excavator and simulate a working cycle of excavator in PTC Creo to find reaction forces on the joints of boom and stick as well as determine the driving forces in the hydraulic cylinder of the bucket, stick and boom.

## 2. Method of study

***Basic parameters of excavator model:***

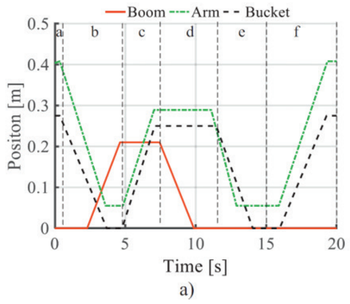
Standard excavators come in a variety of sizes, from mini excavators that are perfect for tight job sites to large excavators designed for heavy-duty applications. Bucket, stick and boom for standard excavators are also available in different sizes and lengths to tackle a variety of tasks, including digging, trenching, moving debris, hauling heavy materials, and demolishing structures. Standard excavators are useful in construction, landscaping, mining, farming, forestry, and other industries that require excavation (Gregory Poole CAT, 2020). In the scope of this study, a track excavator is selected with the technical specifications in Tab. 1 (Kato works co.,ltd, 2020).

***Determination of masse and centre of gravity:***

In addition to breakout and digging forces, the weights of bucket, stick, boom, and material in each bucket must be specified and assigned in the excavator model. Mass properties such as area, volume, and the coordinates for the centre of gravity of solids are translated as test properties and saved as parameters in PTC Creo. When the solid models, related to the file formats for CATIA V5, Creo Elements, NX, SolidWorks, Autodesk Inventor and STEP, are imported, model parameters are created for the imported elements. Creo calculates the validation property values and stores the calculated values of the validation properties for geometry and assemblies in the model parameters (Creo Parametric, 2020). Therefore, the designer must not calculate the masses and centre of gravity as well as inertia of bucket, stick, and boom.

***Calculation of breakout and digging forces:***

Material such as soil, coal, gravel is penetrated to the bucket by the breakout force ($F_B$) and digging force ($F_S$).



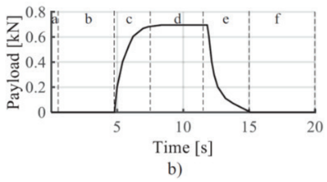




Fig. 3. a) Position-time diagram; b) Payload-time diagram (Zimmerman et al., 2007)
Rys. 3 a) Wykres pozycja-czas; b) Wykres ładunek-czas

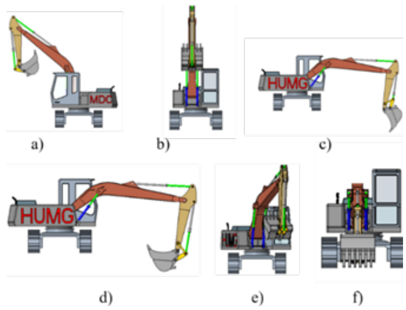



Fig. 4. Operating sequence of a working cycle
Rys. 4. Sekwencja działania cyklu roboczego

These maximum forces can be calculated by the max. The discharge pressure of the pump in the excavator, which provides these forces to the hydraulic bucket and stick cylinders. Maximum breakout force $F_B$ is generated by the bucket cylinder and tangent to the arc of radius $d_D$ (Patel, B.P., Prajapati, J.M, 2012).

$$F_B = \frac{p \cdot \pi \cdot D_B^2 \cdot d_A \cdot d_C}{4 \cdot d_D \cdot d_B} \tag{1}$$

where: $d_A$, $d_B$, $d_C$, $d_E$, $d_F$ - the distances and labeled in Fig. 2; $D_B$ – the diameter of the bucket cylinder $D_B$ =120 mm; p – max. discharge pressure of pump, p=32.4 MPa

Maximum digging force $F_S$ is generated by the stick cylinder and tangent to the arc of radius $d_F$ (Patel, B.P., Prajapati, J.M, 2012).

$$F_S = \frac{p \cdot \pi \cdot D_S^2 \cdot d_E}{4 \cdot d_F} \tag{2}$$

where: $D_S$ – the diameter of the stick cylinder $D_S$ =135 mm

The values of parameters in equations (1), (2) are measured in 3D-Cad excavator model and hold as $d_A$=425 mm, $d_B$=540 mm, $d_C$=370 mm, $d_D$=1295 mm, $d_E$=645 mm, $d_F$=2980 mm. By using the equations (1), (2), the breakout and digging forces are calculated $F_B$=82357 N=82.357 kN and $F_S$=100328 N=100.328 kN.

***Determination of bucket capacity:***

The capacity of a bucket $V_S$ muss be calculated by its measuring dimensions. In this example, it holds the value of 0.8 m³. The excess material capacity is determined by the material to fulfill factor, and it depends on the kind of material (Rusiński, E., Czmochowski, J., Moczko, P., Pietrusiak, D., 2017). In this example, the material is rock, well blasted $f_f$=0.9, and density ρ=1600 kg/m³. Therefore, the weight of material in bucket P=1152 N.

***The working cycle of excavator:***

Cycle time for the excavator depends on the movements of the swing system, boom, sticker (arm), and bucket. The relative positions of these movements are commonly described in a position-time diagram. In this diagram, the movements will be divided to different phases, the start and end of each position correspond to start and end time of each movement (see an example in Fig. 3 a). Moreover, to determine the driving forces of the boom, stick, and bucket cylinders as well as reaction forces, a loading profile must be shown. According to J.D. Zimmerman (D. Zimmerman, M. Pelosi, C.A. Williamson, 2007), a charging payload holds a value up to 60% working cycle (Fig. 3 b).

A working cycle of excavator is the input reference for the dynamic simulation. The relative positions of bucket, stick and boom are driven by three hydraulic cylinders. The movement of each cylinder decides the working ranges and is

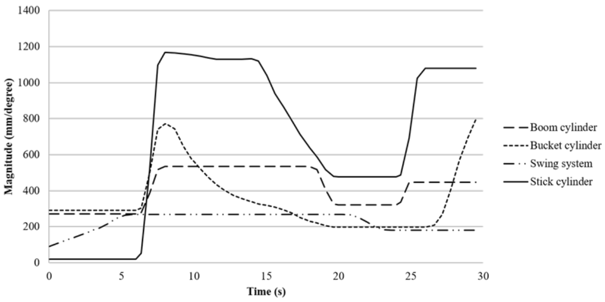



Fig. 5. Working cycle diagram of the bucket, stick, boom cylinders and swing system

Rys. 5. Schemat cyklu roboczego łyżki, ramienia, siłowników wysięgnika i systemu obrotu

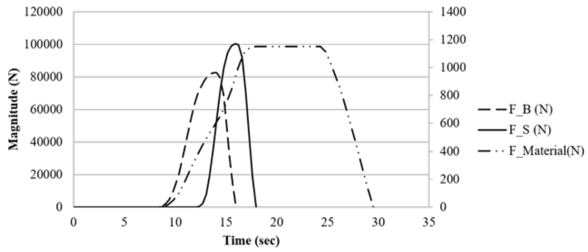



Fig. 6. Breakout, digging forces and gravity of material on the bucket

Rys. 6. Siły wyrwanie, kopania i ciężar materiału na łyżce

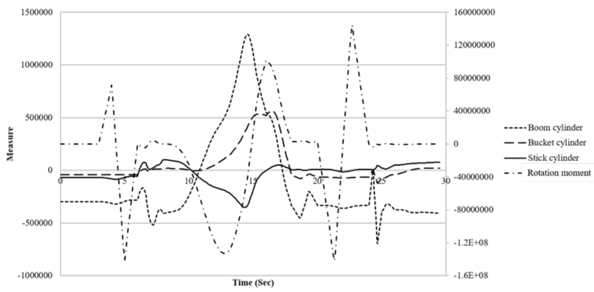



Fig. 7. Driving forces/moment diagram of the bucket, stick, boom cylinder and swing system

Rys. 7. Wykres sił napędowych / momentów łyżki, ramienia, siłownika wysięgnika i układu obrotu

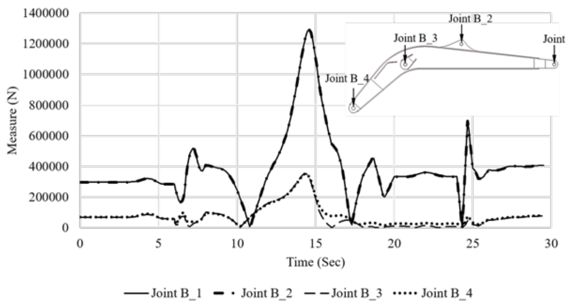



Fig. 8. Joint reaction forces of boom

Rys. 8. Siły reakcji bomu na przegub

described in a position-time diagram. Normally, experienced operators have an average cycle time of 24.5 s to perform a similar trenching cycle with a 20-tonne excavator (Zhang, S., Minav, T., Pietola, M., Kauranne, H., Kajaste, J., 2019). The average cycle time for the excavator was 29.5 seconds by using a mining excavator Terex RH 200. The average swing time for an empty bucket is 7.5 seconds (25%). The machine needs 12 seconds (41%) to fill the bucket. The average swing time for the full bucket is 7 seconds (24%). It takes the excavator 3 seconds (10%) to dump its load (Fiscor, S, 2020). Therefore, in this paper, a cycle time of 29.5 s was utilized for this excavator model. The typical moving cycle consists of six steps and is shown in Fig. 4.

a) Beginning position

b) Rotating to a minimum reach position

c) Rotating, lowering the boom, the stick and opening the bucket simultaneously

d) Digging a bucketful of material

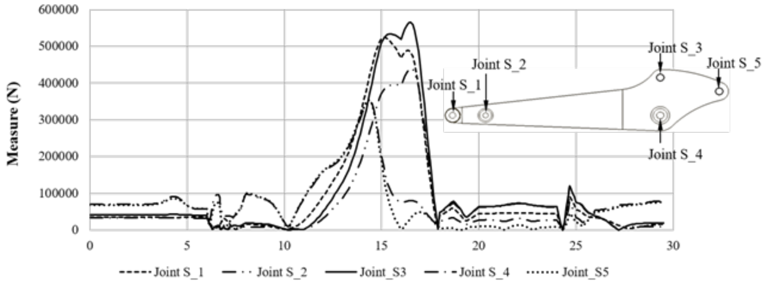



Fig. 9. Joint reaction forces of stick

Rys. 9. Siły reakcji ramienia na przegub.

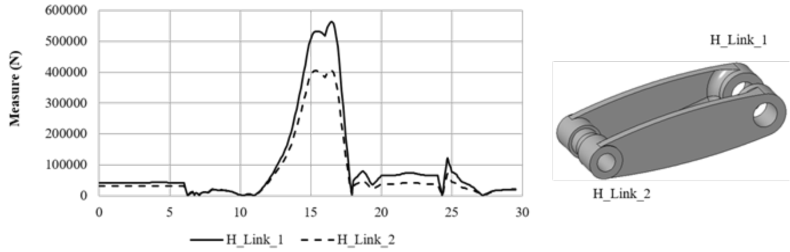



Fig. 10. Joint reaction forces of H_Link

Rys. 10. Siły reakcji z H_Link na przegub

e) Lifting the boom and rotating to discharging position

e) Lowering the boom, opening the bucket, and discharging material

In a working cycle 29.5 s, each position of a cylinder is determined by moving time. To simulate the hydraulic excavator, all positions of the bucket, stick, boom cylinders, and angles of the swing system must be established. The operating sequence in Fig. 4 is used to define these positions/angles. They must ensure the smooth movement of the excavator and are suitable for the working requirements. For this study, the relationship between the positions of the bucket, stick, boom cylinder, as well as the angle of the swing system is shown in Fig. 5.

In this working cycle of the excavator, the stick cylinder moves with a max—stroke 1150 mm at the time of digging material. The bucket cylinder holds a max stroke 780 mm at the time of burrowing and discharging. The max stock value of boom cylinder is 530 mm at the time of discharging material. The swing system rotates 180 degrees from the start position to the discharging material position. The positions of the bucket, stick, boom cylinders, and swing system depend on each other according to the working cycle.

***Definition of loads on the bucket:***

An operating sequence of the excavator will be simulated according to the cycle time 29.5 s. Weights and direction gravity of the bucket, stick and boom are assigned to them in the whole working cycle. However, the breakout force, digging force only exist in a digging process and depend on the working cycle time. Fig. 6 shows the breakout force, digging force. The loading time takes along 12 s, between 8 s and 20 s. Material on the bucket is determined from the charging time to the discharging time. The gravity of material on the bucket is displayed in Fig. 6.

**3. Simulation results and discussions**

Driving forces/moment of the bucket, stick boom cylinders, and swing system:

The weights of bucket, stick, boom, and material on the bucket are smaller than the breakout and digging forces. Therefore, the driving forces of bucket, stick, boom cylinders at the time of digging material are much bigger than other time. Their value reaction forces are shown in Fig. 7.

The maximal driving forces of the bucket, stick, boom cylinders are calculated as 564785 N, 353474 N and 1290184 N.

After loading material, the swing system rotates 90 degrees to the discharging position. With full of material on the bucket, the torque of the swing system gets the maximum value of 144670799 Nmm (see Fig. 7).

***Reaction forces on the joints of boom and stick:***

The boom rotates on the pin Joint B_4, the stick rotates on the pin Joint B_1. The double effect hydraulic cylinder allows to raise and lower the boom. The boom motion around Joint B_4 can be related to the variation of angle (Eugenio Leati, Roberto Paoluzzi, 2010). The boom of excavator contains 4 joints and are shown in Fig. 8. The joint B_3, and B_4 connect to the boom cylinder and upper structure. Therefore, the reaction forces of these joints are the same value. The Joint B_2 connects to stick cylinder, the Joint B_1 links to the stick. The curve of these reaction forces on B_1 is similar to the curve of B_2. During a digging material, the joint reaction forces hold the maximum values and are calculated as S_1 = 1289928.334 N, S_2 = 1290584.244 N, S_3 = 353425.518 N and S_4 = 351038.93 N.

The stick rotates on the pin Joint S_4, and bucket linkage goes around on the pin Joint S_1. Stick cylinder allows to extend and retract the stick, while the bucket cylinder allows to open and close the bucket. The stick of excavator links to the bucket and stick cylinders. It comprises five joints S_1 to

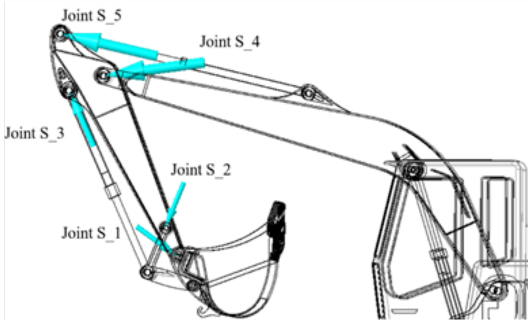


Fig. 11. Directions of joint reaction forces of the stick at the beginning position
Rys. 11. Kierunki sił reakcji na przegub w pozycji początkowej

S_5. The boom, arm and bucket are designed for maximum reaction forces during a digging material. The joints S_1, S_2, S_3, S_4 and S_5 are calculated as 523818.45 N, 440100.8 N, 565220.54 N, 351038.93 N and 353591.11 N (see Fig. 9).

H_Link joins the bucket cylinder by H_Link_1 and bucket by H_Link_2. The curves of reaction forces are similar, but the values of H_Link_1 are little bigger (see Fig. 10). Reaction forces on these joints alter in a working cycle. The values of the reaction force of each time of H_Link_1 are bigger than H_Link_2.

In a working cycle, the reaction forces not only alter the magnitudes but also charge the directions. The Fig. 8 to Fig. 10 show all of reaction force magnitudes of each joint of the boom, stick and H_Link. However, to determine the stress of them by using FEM (Finite Element Method), it requires to define all directions of reaction forces according to the working cycle. It means, the equilibrium condition of the boom, stick and H_Link muss be established for every position in the working cycle. The equilibrium condition of an object exists when Newton's first law is valid. An object is in equilibrium in a reference coordinate system when all external forces (including moments) acting on it are balanced. This means that the net result of all the external forces and moments acting on this object is zero (XiaoboYang, PeijunXu, 2012).

By utilizing the method of equilibrium condition to find the directions of reaction forces, it takes a lot of time. Hence, dynamic simulation is applied to find them quicker.

Fig. 11 shows the directions of reaction forces of joints S_1 to S_5 of stick at the beginning position as an example, which are indicated by blue arrows. At this position, gravities of the bucket, stick and driving forces of the stick and boom cylinder influence these joints. Based on

Fig. 11, the designer can fix the direction and magnitude of the reaction force and then calculate stress.

Creo parametric is used in this paper to establish the 3D-CAD model and calculate the driving and joint reaction forces of the hydraulic excavator. In order to improve the simulation accuracy, users have to accurately define the links and joints, external forces acting on the excavator in a working cycle. In the study of Šalinić (S. Šalinić, G. Bošković, M. Nikolić, 2014), they used the mathematical method to determine the forces in the bucket, stick and boom cylinders. It is taken that the time interval of the considered digging task reads $0 \leq t \leq 3$ s, the digging force varies and gets the max value of 20.5 kN. The driving forces of the hydraulic bucket, stick, and boom cylinders also alter according to this time interval and hold the max values of 120 kN, 150 kN and 200 kN. In this study, the breakout and digging forces are five times bigger than the above example. Therefore, the driving forces are approximately bigger than five times.

**4. Conclusions and proposals**

A working cycle of excavator consists of multiple movements of the bucket, stick, boom cylinders and swing system. The values of driving forces and reaction forces depend on the positions of drive elements. The driving/reaction forces as well as the acceleration, velocity typically can be calculated by analytic geometry and mathematical method. However, it is complex and takes a lot of time. In this study, the position-time diagram is used to describe the motions of excavator in a working cycle, then the external loads (gravities, break out and digging forces) are declared and assigned them to components of the excavator.

Based on the 3D-Cad model, the design parameters such as the masses, moments of inertial and dimensions of the boom, stick, bucket, swing system are quickly determined as well as the input parameters are defined. 3D modeller reduces project cost margins for machinery maker.

Dynamic simulation in PTC Creo is applied to calculate and plot the driving forces/moment and joint reaction forces. On the grounds of the diagrams, the designer can easily find out the maximum value on each joint and required driving forces/moment of drive components.

Dynamic simulation can be used not only for the design of track excavator but also for the design of any machine or equipment and reduce the time from the first idea to the delivered device.

**Literatura – References**

1. Alaydi, Juma Yousuf. ‚Modeling and simulation of a hydraulic excavator, 2009
2. Belma Babovic, Almir Osmanovic, Bahrudin Saric., Design and simulation of hydraulic excavator manipulator system, XVII International Scientific Conference on Industrial Systems, Novi Sad, Serbia, October 4. – 6. 2017, pp. 108-111.
3. Bhaveshkumar P. Patel, J. M. Prajapati, Dynamics of Mini Hydraulic Backhoe Excavator: A Lagrange-Euler (L-E) Approach, International Journal of Mechanical, Industrial Science and Engineering Vol:8 No:1, pp. 202-211, 2014
4. Creo Parametric, Mechanism Design and Mechanism Dynamics, Internet http://support.ptc.com/, 2020.
5. Eugenio Leati, Roberto Paoluzzi., Hydraulic Excavator Working Cycle: From Field Test to Simulation Model, 7th International Fluid Power Conference, Aachen 2010
6. Fiscor, S., Better technology and more power make loading tools more productive, but well-trained operators are the most important aspect, Productivity Considerations for Shovels and Excavators, internet: http://www.womp-int.com/, 2020
7. Gregory Poole CAT., Excavator types, internet: https://www.gregorypoole.com/, 2020
8. Korucu, S., Küçük, A. E., Samtaş, G., mini excavator design and analysis, International Journal of Innovative Science and Research Technology, Volume 2, Issue 11, November– 2017, pp. 198-206
9. Kato works co.,ltd., Regzim fully hydraulic excavator HD820R, internet: http://www.kato-works.co.jp, 2020
10. Mishra, R., Dewangan, V, optimization of component of excavator bucket, International Journal of Scientific Research Engineering & Technology, May 2013, Volume issue 2, pp. 76-78
11. Orlemann, E.C., power shovels, the world's mightiest mining and construction excavators, motor books international, 2003, pp. 101-102.
12. Patel, B. P., Prajapati, J.M., soil-tool interaction as a review for digging operation of mini hydraulic excavator, international journal of engineering science and technology, 2011, vol. 3, no.2, pp. 894-901.
13. Patel, B.P., Prajapati, J.M., evaluation of bucket capacity, digging force calculation and force analysis of mini hydraulic backhoe excavator, machine design, 2012, vol. 4, no. 1, pp. 59-66.
14. Rosen Mitrev, Dragoslav Janošević, Dragan Marinković., Dynamical modelling of hydraulic excavator considered as a multibody system, Technical Gazette 24, Suppl. 2(2017), 327-338
15. Rusiński, E., Czmochowski, J., Moczko, P., Pietrusiak, D., Surface Mining Machines, Springer International Publishing, 2017
16. Salcudean, S.S, Tafazoli, S., Lawrence, P.D., Chau, I., impedance control of a teleoperated mini excavator, advanced robotics icar '97 proceedings 8th international conference, monterey, california, u.s.a., 1997, pp. 19-25.
17. Zhang, S., Minav, T., Pietola, M., Kauranne, H., Kajaste, J., The effects of control methods on energy efficiency and position tracking of an electro-hydraulic excavator equipped with zonal hydraulics, Automation in Construction, 2019, Volume issue 100, pp. 129-144
18. J.D. Zimmerman, M. Pelosi, C.A. Williamson., Energy Consumption of an Ls Excavator Hydraulic System, ASME International Mechanical Engineering Congress &Exposition, Seattle, Washington, USA, November 11–15, 2007
19. XiaoboYang, PeijunXu., Road Load Analysis Techniques in Automotive Engineering, Chapter 1, pp. 1-60, Butterworth-Heinemann, 2012.
20. S. Šalinić, G. Bošković, M. Nikolić., Dynamic modelling of hydraulic excavator motion using Kane's equations, Automation in Construction 44 (2014) 56–62.

## *Dynamiczna symulacja koparki hydraulicznej w celu określenia sił reakcji na przegub, wysięgnik, ramienia, łyżkę oraz sił napędowych cylindrów hydraulicznych*

*Określenie siły reakcji na przegub i siły napędowej jest warunkiem optymalizacji wymiarów wysięgnika, ramienia koparki hydraulicznej i dobrać odpowiednie hydrauliczne siłowniki łyżki, ramienia i wysięgnika. W cyklu roboczym koparki, siły te zawsze zmieniają się. Tradycyjne metody są zwykle skomplikowane i trudne do określenia maksymalnych sił reakcji, które mogą spowodować złamanie drążka i wysięgnika. W artykule zbudowano model 3D i symulowano cykl pracy koparki hydraulicznej w celu znalezienia wykresów sił reakcji wysięgnika i ramienia oraz sił napędowych cylindrów hydraulicznych za pomocą oprogramowania komputerowego PTC Creo Parametric. Na podstawie tych wyników, konstruktor w łatwy sposób oblicza maksymalne naprężenia wymiarów wysięgnika i ramienia w cyklu pracy, aby zoptymalizować ich wymiary, a także dobiera odpowiednie hydrauliczne cylindry.*

**Słowa kluczowe:** *symulacja dynamiczna, projektowanie koparek, siły reakcji na przegub, siły napędowe, maksymalne napięcie*