SIMULATION AND ANALYSIS OF THE KINEMATICS OF A SINGLE BUCKET HYDRAULIC EXCAVATOR DURING THE EXCAVATION PROCESS

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Abstract: In the extractive industry, single bucket hydraulic excavators are used to extract loads of material from silos or dumps, move and unload these on to the transportation means. Single bucket hydraulic excavators can also be used to make embankments and dikes, to dig foundations, ditches and roadbeds. Their operating performance, such as work space, technological forces, cutting and loading capacity, are closely related to the structure and operation, kinematics and dynamics of the bucket-arm mechanism, which can be assimilated with a spatial manipulator with 4 degrees of freedom (DoF). This offers the possibility to use the theory of manipulators, adapted to the specific destination of hydraulic excavators, in order to model and simulate them. For the simulation and study of kinematics in this paper, the Hyundai R30Z-9AK mini-excavator arm model was developed in the SOLIDWORKS® application.

Keywords: mechanisms, DoF, hydraulic excavator, arm, kinematics

1. INTRODUCTION

Single bucket hydraulic excavators are machines used for excavating and loading ore or rock materials in mining and construction. The working tool of these machines is the bucket. The components of a single bucket hydraulic excavator are shown in Figure 1. One can see the lower frame or under carriage, with the tracked movement mechanism - A, which supports all the assemblies and mechanisms of the excavator while ensuring its displacement. The rotating platform - B is connected to the under carriage - A and it rotates by means of rollers or balls. On this platform are mounted the drive motor, the bucket lifting mechanisms, the excavator rotation

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mechanism, the hydraulic cylinders that determines the variation of the articulated bucket arm length during the loading and unloading process, drive systems and the control cabin. The working equipment (hoe) consists of the boom - 1, the dipper arm - 2 and the bucket - 3.

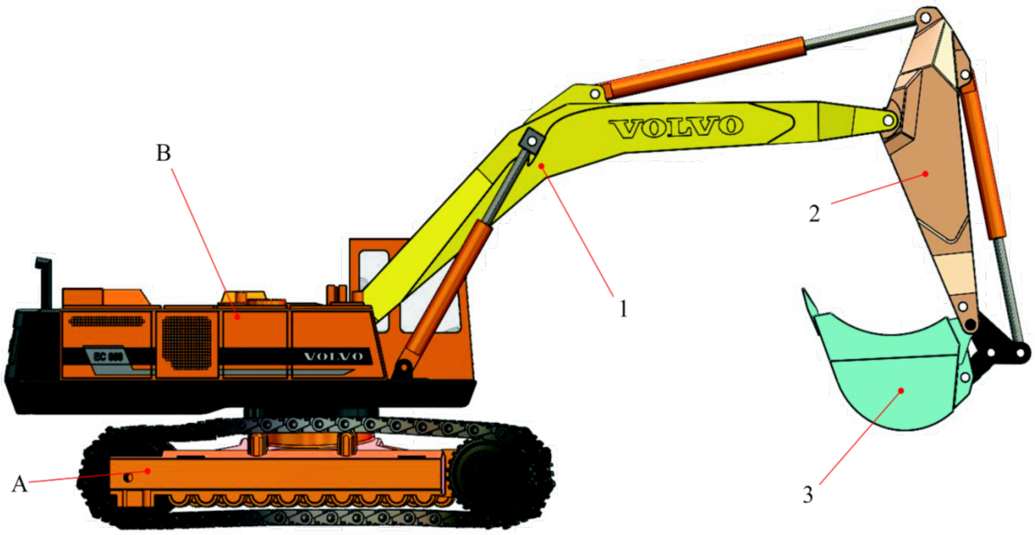

Fig. 1. Single bucket hydraulic excavator

2. THEORETICAL ASPECTS REGARDING THE POSITIONING KINEMATICS OF THE HYDRAULIC EXCAVATOR

Figure 2 shows the working equipment of a hydraulic excavator. This works like a manipulator with 4 degrees of freedom.

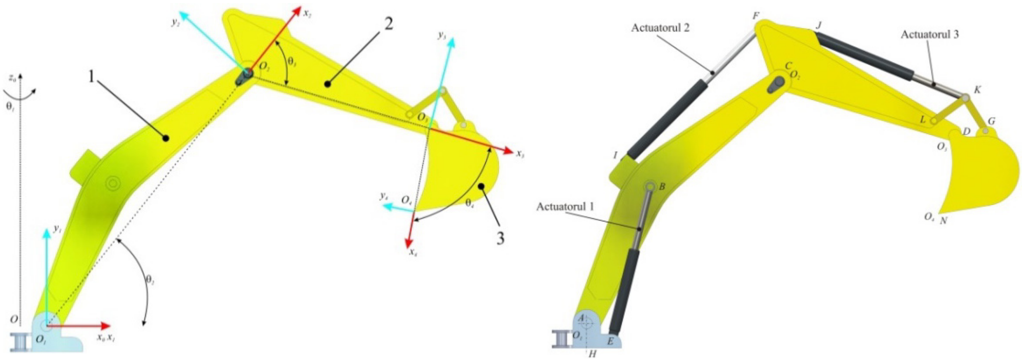

Fig. 2. Hydraulic excavator working equipment,
coordinate systems attached to it and positions of hydraulic cylinders

During the movement, the bucket of the excavator moves on a trajectory described by its position in the working space, depending on the values of the rotation angles in the kinematic joints. The magnitudes of the angles of rotation are determined by the magnitudes of the displacements of the piston rod of the hydraulic drive cylinders which behave like actuators. Thus, the hydraulic cylinders together with their command and control system represent the hydraulic actuators.

In relation to a fixed reference system, the position of the excavator bucket can be expressed in Cartesian coordinates or in robot coordinates, which represent the coordinates of the kinematic joints, being expressed by the rotation angles of the kinematic joints θ_i. It can be seen that in the workspace, the position of the bucket is determined by the coordinates of point O_3. This is the origin of the mobile reference system $Ref(O_3, x_3, y_3, z_3)$. During excavation which involves cutting material from the massif, the excavator arm moves only vertically so that the angle θ_1 is constant.

The orientation of the bucket can be expressed in terms of the rotations of the axes of the reference system $Ref(O_4, x_4, y_4, z_4)$ in relation to the axes of the reference system $Ref(O_3, x_3, y_3, z_3)$ using Euler's angles. The positions of the pistons of the hydraulic cylinders determine the angles of rotation in the joints but also the configuration of the arm and the position of the bucket. The length of the line segment between the connecting points of the hydraulic cylinders represents the length of the hydraulic actuator. From this point of view, it is important to establish the connection relations between the actuator lengths and the rotation angles in the joints. In figure 2 the first hydraulic cylinder has the rod placed in point *B*, thus producing the rotation of the joint 2. The length of the hydraulic cylinder L_{BE} is the length of the segment *BE*, which can be expressed according to the value of the angle θ_2:

$$L_{BE}^2 = \left[L_{AB}\sin\left(\theta_2+\beta\right)+L_{AH}\right]^2+\left[L_{AB}\cos\left(\theta_2+\beta\right)-L_{HE}\right]^2 \tag{1}$$

where β is the constant angle between the segments *BA* and *AC*.

The dimensions L_{BE}, L_{AH} and L_{HE} are constructive data of the analyzed single bucket hydraulic excavator, so these segments have constant values.

3. PRESENTATION OF THE PROPOSED MODEL

The Hyundai R30Z-9AK mini-excavator is used as a model in order to study of the excavation kinematics of a single bucket hydraulic excavator. The characteristics of this machine are presented in table 1.

Table 1 **Characteristics of the excavator**

Model	Hyundai R30Z-9AK mini excavator
Operational weight	30,000 N
Engine power	18.5 kW / 25 hp at 2350 rpm
Bucket capacity	0.03 m^3
Excavation depth	2,500 mm

SOLIDWORKS® application was used to create a virtual model of the working equipment of this mini excavator at 1:1 scale. The overall dimensions are shown in figure 3.

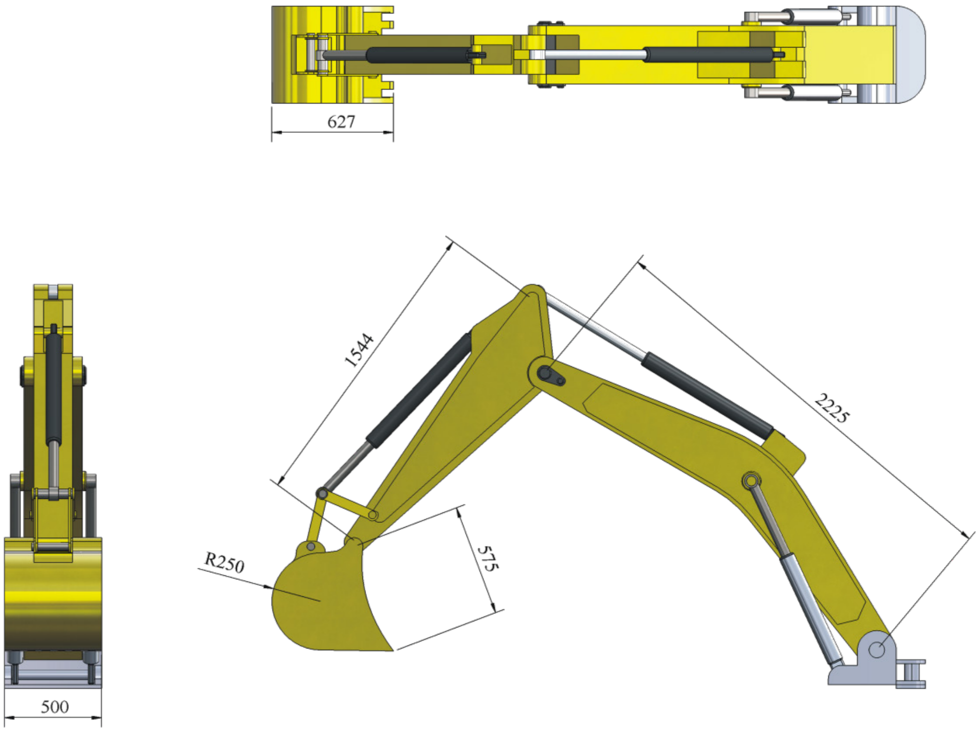

Fig. 3. Dimensions of the model of the excavator working equipment (in millimetres)

4. SIMULATION OF THE KINEMATICS OF THE WORK EQUIPMENT MODEL

In order to be able to simulate the excavation process, but also the material discharge process, a linear motor operating between the end of the piston and the bottom of the cylinder, was attached to each of the three hydraulic drive cylinders. The equations of motion were imposed by mathematical expressions using the *step* function which is implemented in the SOLIDWORKS® software library:

$$\mathrm{STEP}\left(a, x_1, y_1, x_2, y_2\right) = \begin{cases} y_1, & a \leq x_1 \\ y_1 + \left(x_2 - x_1\right)\left(3 - 2z\right)z^2, & x_1 \leq a \leq x_2 \\ y_2, & a \geq x_2 \end{cases} \tag{2}$$

$$z = \frac{a - x_1}{x_2 - x_1}$$

The pivoting movement of the mini excavator arm is performed by means of a rotary motor, also specific to the software used. Figure 4 shows a Gantt chart highlighting the time sequence of the action of the four actuators that determine the kinematics of the working equipment of the mini excavator, while Figure 5 shows the variation of the space traveled by each piston of the drive cylinders. We specify that for the first actuator (the linear drive motor of the boom) the second ordinate axis (the right one) was used.

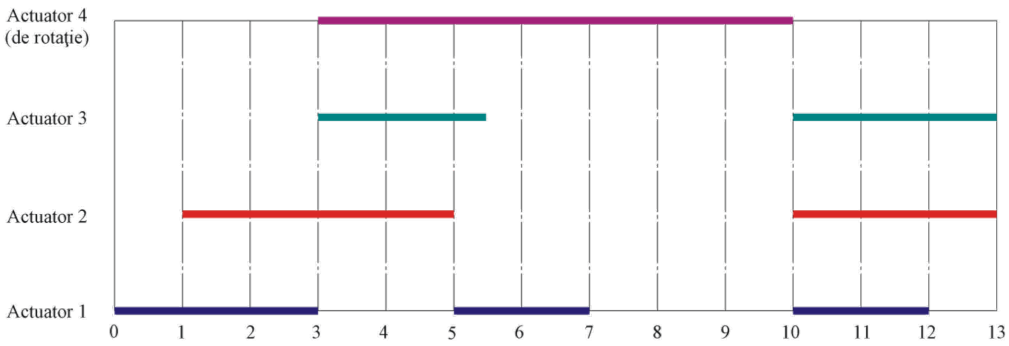

Fig. 4. Gantt chart highlighting the time sequence of the action of the four actuators

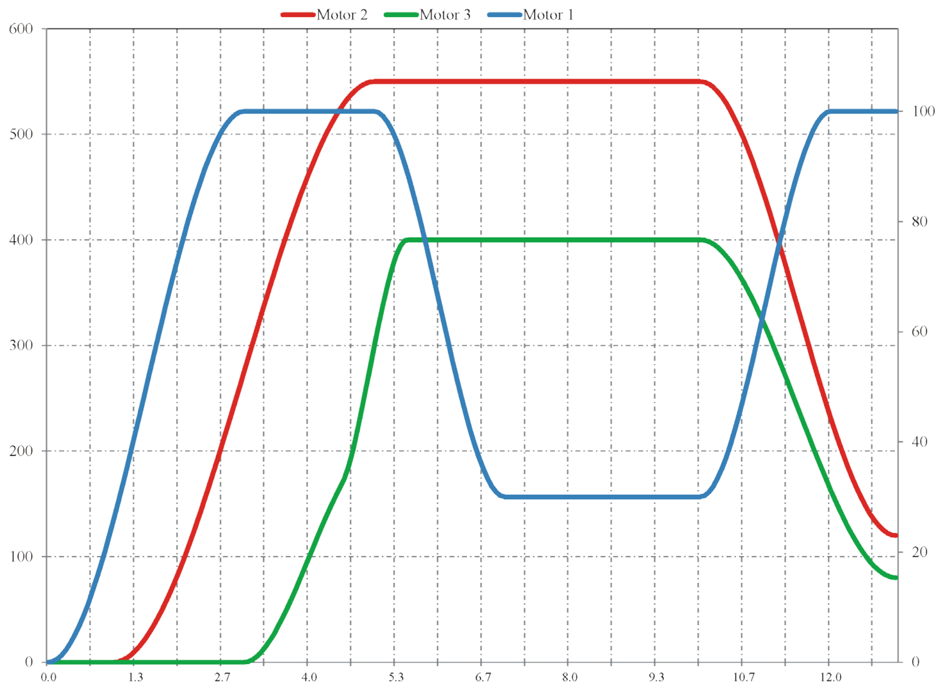

Fig. 5. Diagrams of the variation of the space travelled by each piston of the drive cylinders

After simulating the complete process of lowering the bucket, excavating material, lifting, transporting and discharge of the excavated material, the first result obtained is the trajectory of a tooth on the bucket of the mini excavator, as it can be seen in Figure 6. We emphasize that this trajectory is the result of a specific excavation scheme, not being unique.

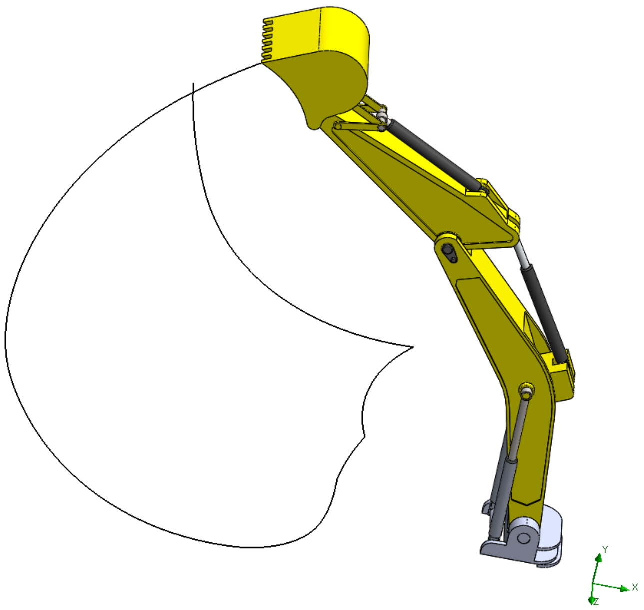

Fig. 6. The trajectory of a tooth from the bucket of the mini excavator

For the obtained trajectory we determined the technological volume (figure 7) with the aid of SOLIDWORKS® software tools. All points corresponding to a 3D trajectory (of the point on the tooth in this case) expressed as coordinates in each direction: x_i, y_i and z_i were exported to a *.csv* file that was imported into MSExcel. Using the mathematical functions MIN and MAX of Excel, we determined the limits of the coordinate variation for the three directions *X*, *Y* and *Z* as can be seen in Table 2. With these values the lengths of the edges of the parallelepiped which represents the technological volume of the excavation (volume occupied by the excavator working equipment) were determined.

Table 2 **Determination of the edge length for the parallelepiped (technological volume)**

Limits on direction X (mm)		Limits on direction Y (mm)		Limits on direction Z (mm)	
Min	Max	Min	Max	Min	Max
-4075	-1355	-293	3422	-3103	-101
Length of edge X (mm)		Length of edge Y (mm)		Length of edge Z (mm)	
2721		3726		3003	

Based on the values computed in table 2, it results that the technological volume (volume occupied by the excavator working equipment) is $V_{TH} = 30.35\ m^3$.

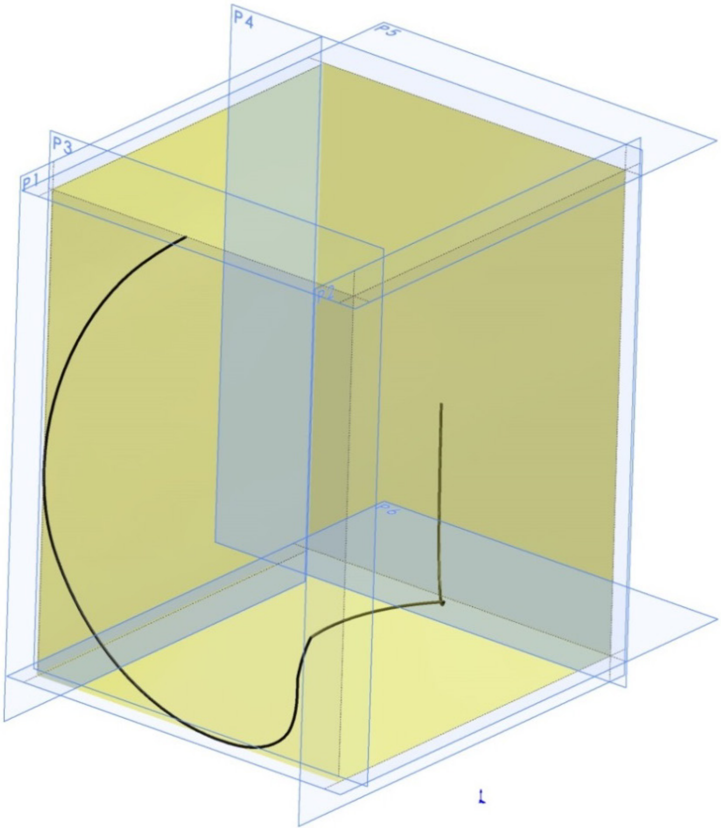

Fig. 7. Representation of the technological volume

5. CONCLUSIONS

A virtual model of a mini-excavator was built to study the kinematics of the work equipment during excavation. The model was developed as a set of parts between which geometric connections of coincidence, concentricity and distance were established.

The study was conducted in SOLIDWORKS® software, using the *Motion Analysis* type study of the *Motion Study* menu.

Rotary or linear motors have been attached to the virtual model moving parts, for which the equations of motion can be expressed by constant velocities, distances traveled in certain time intervals, periodic oscillations, trajectory segments, points, as well as by mathematical expressions.

In order to highlight the time sequence of the action of the four actuators producing kinematics of the excavator working equipment, a Gantt chart was used, then the variation of the space traveled by the piston of each hydraulic drive cylinder was graphically represented.

The simulation of the excavation process was performed, which includes the following sequence: lowering the bucket, cutting, lifting, transporting and discharging the excavated material. Based on this the spatial trajectory of a tooth on the excavator bucket was obtained for a certain excavation scheme. For this trajectory, the size of the technological volume (of the working space in the terminology of the manipulator theory) was determined, respectively the volume that frames the trajectory of the bucket.

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