An open-loop vs. closed-loop backhoe excavator control system

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Abstract: The excavation process has got two main features. The first one is the soil digging. It can be regarded as a quasi-static process in fact, in which the acceleration could be neglected. The second one is the soil transportation and bucket discharging. It can be considered as a dynamic process. Some parts of these features would be automated. There are two main control systems, open and closed-loop control. The main aim of the paper is to present the application of these two systems and compare them. The control systems were tested during the digging process. It begins with the bucket on the primary digging position and ends when it is filled. The paper starts with description of the excavator control systems components. They have got hierarchical structure. The first is the hardware level: sensors, actuators, valves. The PLC executes a direct control on this level. The links between objects would be realized via CAN network. The excavator's control system realizes a simple excavator's bucket motion along prescribed trajectory algorithm. The software level assures calculation of the trajectory parameters, i.e. coordination of the milestones. The bucket velocity was the input quantity. It means that the valve's spool displacements are calculated for each actuator separately. Machine counterbalance and actuators parameters would be the limits of the process. The results of the two systems testing procedure would be presented and compared.

Keywords: excavator, control system, open closed loop

1. INTRODUTION

The min excavator's control systems were the object of testing. Its technical feature were shown on the Fig. 1. main idea of the control systems. The force variation is a result of stochastic soil properties.

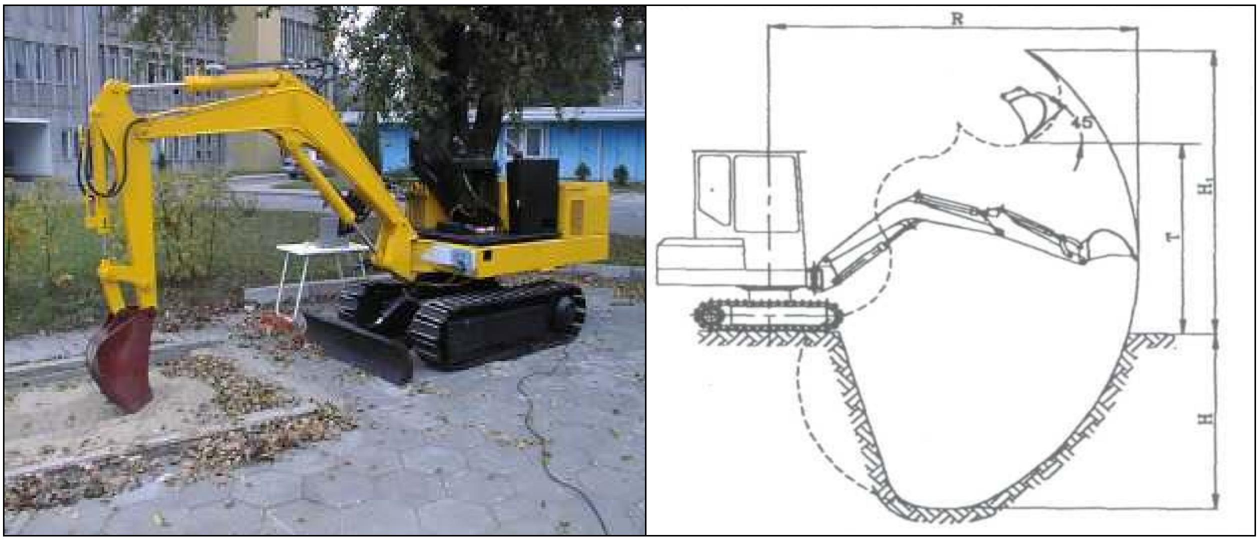

Fig. 1. K-111 excavator on site and its technical features

The excavator has got the typical hydraulic system. The PVG 32 with CIP element has been applied. The CAN network was used for spool's movement.

The two control systems, open and closed, were examined. TCP - tool central point movement along prescribed path is a result of attachment elements relative rotation. It is forced by the actuators length changing. It is means that the bucket motion is proportional to oil volume pumped to cylinders. The independent control of the hydraulic cylinders is the

The excavator bucket has got three degrees of freedom. Due this, with lack of lashes, the length of the cylinders determinates its location unambiguously.

It is set with the two bucket's co-ordinates *x,z* and the angle between the normal to the trajectory which it moves along.

The main idea of the control system consists on the equipment hydraulic cylinders independent operating [2]. This system conquests the small obstacles appearing during the soil cutting process.

The movement is limited by maximum cylinders forces and the excavator engine power.
In assumption the control system works in automatic mode. The movement equations describe the bucket's movement along the path with following kinematics constrains:

- hydraulic cylinders length;
- the path location in the working area.

Optimization of the bucket trajectory regards with its filling was considered earlier [2],[4],[5].

2. THE CONTROL SYSTEMS

The aim of the control systems is to create and execute of the bucket trajectory. Particularly:

1. creation of the executable trajectory
2. delimitation of the draught of the control value;
3. sending the telegrams to the PLC.

The two control systems were described below.

2.1. Open-loop control system.

It requires to determinate relation between bucket movement and cylinders length.
Dividing trajectory to the finite number of sections and calculate relative to their end points lengths of cylinders makes the cylinders volume changes known. The oil dose should be compared to the valve flow characteristic of the arm, boom and bucket lines. The hydraulic oil volume depends of the movement speed, of course. Open loop control system doesn't comply those factor as valve "dead band", oil temperature, oil pumps output.
The open-loop control system has got following parts: PC computer, PLC control unit, CIP (CAN Interfaced Product) – the A/D converter, PVG32 hydraulic valve with PVE driven spools.

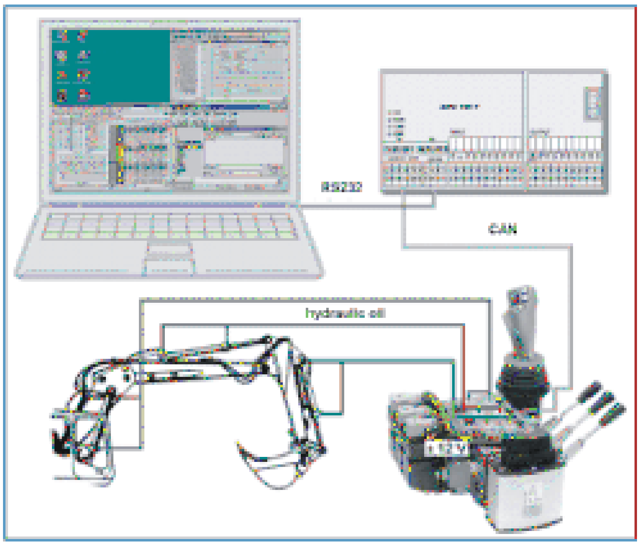

Fig. 2. The open loop control system.

The software, working in the supervising computer, creates trajectory, and due to the movement speed, the controls values are calculated. The values, written to the text file - ASCII code, are sending to the PLC unit. They were stored as the integer values in table mode. In the next step, on the operator's order, all the table values are sending with the particular time increment, via CAN network, to the CIP as so called "telegrams".
The unit converts the digital values to voltage signals for each valve section.
There were two software applications used with this system. The first one was the application, written in Turbo Pascal, which calculates hydraulic doses. It based on trajectory equations. It means as the invert kinematics. The excavator kinematics properties and the number of bucket path sections. The program check the trajectory runnability at first step. As the next, the doses of hydraulic oil are calculate.
The open-loop control system needs manual correction of the valve flow characteristic. The MS Excel was used for this. It makes possible to create the point type charts which based on the set of (x, y). Ii let to change the values of cells through drag of points on the chart. This gave the possibility of the change of the shape of the curve. The second stage polynomial coefficients were sought. The least square method was used. It should be mentioned that control values are calculate for each link and its movement direction separately.

2.2. Valve flow characteristic recognize.

The recognizing of the PVG32 flow characteristic consisted in the measurement of the dislocation of cylinders rod vs time**.** The PLC unit controls the time, in this case. Its assures the time error no more than 1 ms. The measurement of the length was executed with the wind-up measuring tape, with error no bigger then 1 mm.
All measures were done with the same conditions, i.e. engine speed, load.
Appointed in this way relative length changes of the cylinder let recognize relations between value oil flow and the spool position. Example of the characteristic is shown on Fig. 3.

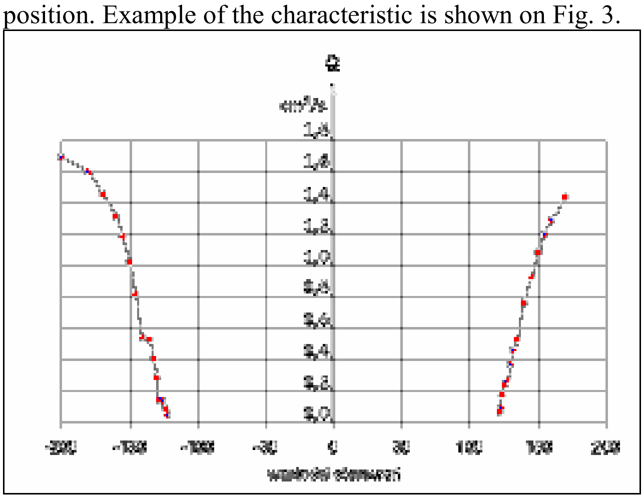

Fig. 3. Example of the PVG32 flow characteristic for the boom lines

2.3. Close-loop control system.

The realization of ***the closed-loop control system*** consists in addition the real bucket location feedback signal to the open-loop system. The rotation encoders were mounted on attachment links. It allows to keep original excavator kinematics. The communication diagram of the system is shown on Fig. 1

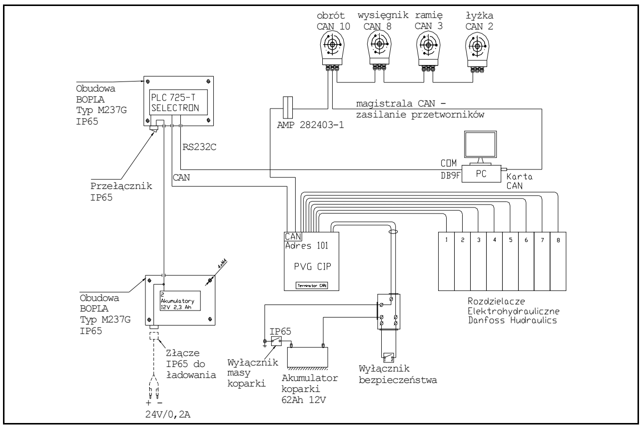

Fig. 4. The communication diagram of the closed-loop system.

The data, describing links configuration in angular mode, are sent to PLC unit. Its software makes two trajectory tables. The first one with angular values for the operator. The second one, in code mode for PLC. The unit's CPU makes every time only one loop. The control values for the each spool are sent in the sequence mode. It doesn't matter, cause the short time of the program execution and slow bucket motion. Some problems may appear with speed optimization and time synchronization.

Software, implemented in PLC, makes following tasks:

- assuring communication with PC via RS232 port – calculated and real coordinates of the trajectory points;
- store the trajectory points coordinates in its memory;
- maintaining the control loop;
- receiving and sending STAR/STOP procedures;
- obtaining the CAN network nodes restart;

The bucket position control simple algorithm was applied. Written in the table trajectory points are sequentially taken as the desire output. They are compared with actual real links positions and the difference between them gives the position error. This is the control value. This calculation loop is cyclically repeated according to the PLC clock frequency – 10 ms. The point achievement condition is check with the same frequency. Every link should be, with *a priori* given margin, at define point. If these criteria are achieved then the next point is taken from the table, the new control value is appointed.

3. Systems tests.

3.1. The way of the tests guidance

Set the rotational engine speed up to 1200 rev/min. Near this speed the hydraulic pump output exceed the required oil flow. So, the changes of rotational speed were neglected. Excavator bucket was placed to the start point manually. It moved along the prescribed trajectory. The trajectory planning problems were not considered during the tests procedure. Otherwise the bucket trajectories were taken *a priori.*

3.2. Trajectory producibility

Horizontal trajectory

Both sets of values given during the experiments are very close to set trajectory. They are closed to the trajectory with ±4 cm margin - Fig. 5. There is a good repeatability for the same set of controls values in the same time. The biggest errors appear in the movement beginning. It is the valve features result, the oil flow divide way. In the beginning the boom cylinder is supplied. The small errors in its lengths make the biggest errors in TCP positions. In the next, when the oil flow is stabilized, the TCP position errors are smaller. However the movement speed was low, it is shown the dynamic influences too, especially in the first part of movement.

Unfortunately after a long brake, for example two days, the trajectory was not achieved.

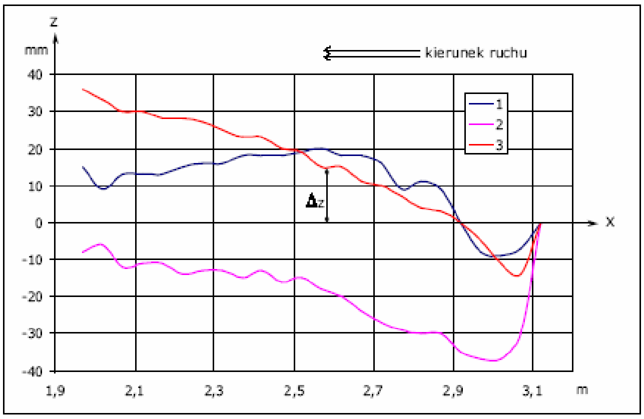

Fig. 5. The horizontal trajectory.

Diagonal trajectory.

The diagonal trajectories are shown on Fig. 6 and Fig.7. The trajectories accuracy is very good. But as was mentioned above it was achieved for particular control values. Otherwise, other trajectory needs another control values.

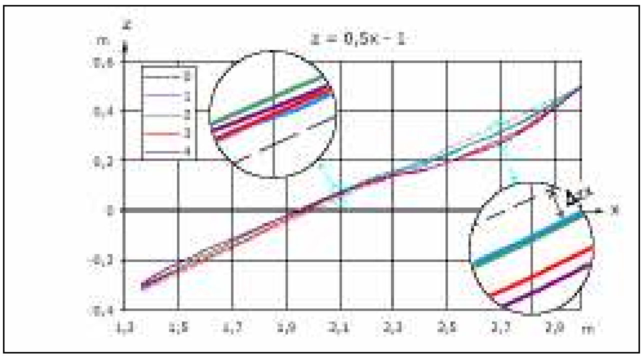

Fig. 6. Diagonal trajectories – open loop.

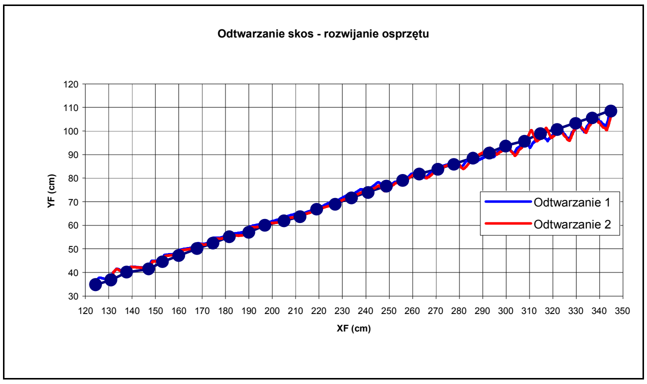

Fig. 7. Diagonal trajectories closed loop.

Vertical trajectory.
As shown on Fig. 8 and Fig. 9, while the vertical trajectories were done, the worst results were achieved.

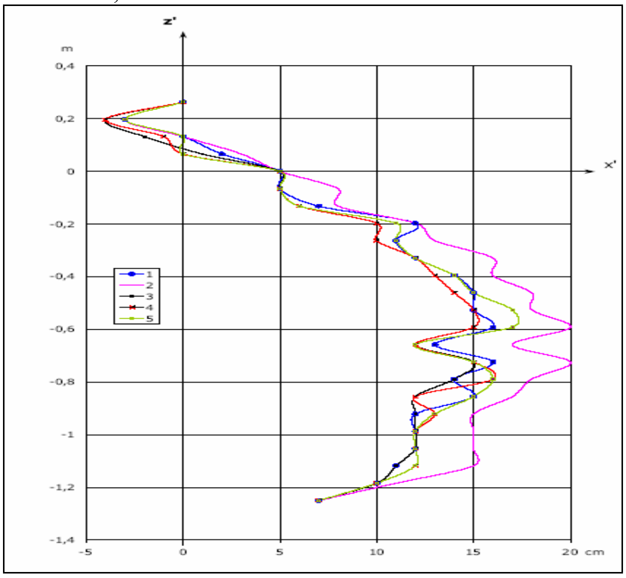

Fig. 8. Vertical trajectories – open loop.

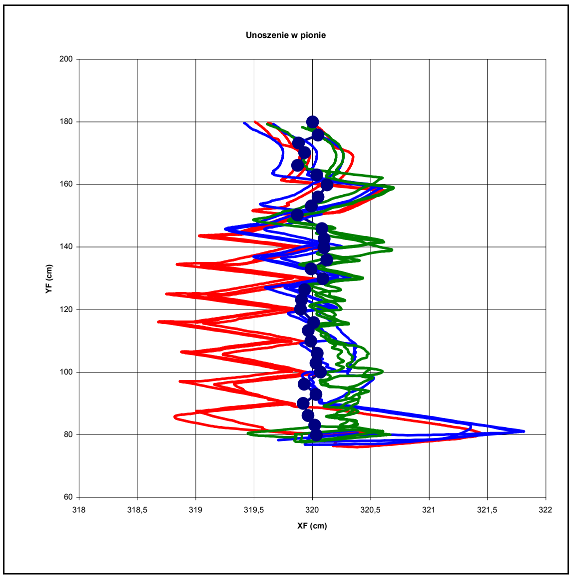

Fig. 9. Vertical trajectory – closed loop.

CONCLUSIONS.

- The open loop trajectories, as shown on Fig. 5, 6, 8, are the parts of sine line. It is a results of the trigonometric relations between the links kinematic;
- The accuracy of trajectories became better while the numbers of trajectory sections increase.
- The boom speed was too fast compare with arm and bucket speed;
- Decrease of boom control values makes better trajectory accuracy until the dead band of the spool would be achieved;
- Closed loop system is time and number of cycles independent;
- Given software makes trajectory preparation easier;
- The open loop control system is cheaper then the closed loop, but more sensitive for the many factors, for example: oil temperature, working time, number of cycles.

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