PID-control Systems on Single-bucket Excavators during Construction Work in Urban Environments

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***Abstract*—Improving digging accuracy is a priority when constructing roads or buildings in urban environments due to infill development and previously laid utilities. The hydraulic shovel excavator is the most versatile construction equipment. The excavator is used on most construction sites of buildings, structures and road network. Improving digging accuracy is being considered for a hydraulic shovel excavator. The current legislation of Russia establishes strict requirements for the accuracy of earthworks, in particular, a shortage of soil less than 0.05 m is allowed. When carrying out earthwork to solve many construction problems, excessive soil removal is not allowed due to a violation of its structure. Modern excavators are equipped with a control system that allows you to assess the external conditions and the position of the working mechanism. To improve the digging accuracy, the author of the article proposes a method for making adjustments to the control system of the excavator working mechanism based on PID control. This method is based on an analysis of excavator position data and several previous positions to better predict changes in excavator bucket edge position.**

***Index Terms*—shovel excavator, mathematical model, PID-control system, accuracy**

I. Introduction

Most earthworks for the construction of roads or buildings in urban environments are done using automation. Hydraulic single bucket excavators are the most versatile automation tool. Single-bucket wheel excavators can be used to solve many different construction problems [1-3].

Russia has strict accuracy requirements. These requirements for the accuracy of earthworks are set out in various standards and laws, such as SNiP of Russia [4-7] (SNiP - building codes and regulations). Such rules take into account the shortage of soil during excavation of no more than 0.05 m.

Failure to comply with these requirements is punishable by law. Accurate estimation of the position of a shovel excavator in digging the trench is necessary as the laying out communications can cause damage to the existing ones, which would cause unacceptable damage to the city. Non-compliance may, for example, lead to a power outage. Power cables were damaged in the Russian banks “Otkrytie” and “Rocketbank” on August 5, 2017 during the improvement of the Sadovy Ring in Moscow for the construction of the My Street program [8, 9]. It was impossible to carry out transactions with a bank card and withdraw cash from an ATM for a whole weekend (August 5 and 6). To meet the established requirements, it is necessary to accurately assess the position of the excavator working mechanism and lay the trench, which will increase the accuracy of the digging process. To solve this problem, it is important to regulate the operation of the excavator systems, which gives signals to control the hydraulic drives of the hydraulic cylinders and affects the position of the pistons of the hydraulic cylinders, which, in turn, affects the position of the cutting edge. excavator bucket. Excavator control can be based on PID control principles.

II. The Principle of PID-regulation

PID-regulation is decoded as proportional-integral-differential controller, therefore, control is introduced by three components:

- P - proportional component, which sets the linear dependence of the control function;
- I - on the integral component, which depends on the antiderivative of the control function;
- D - the differential component, which depends on the derivative of the control function.

The used controller is described by the function of the form:

$$PID(t)=K_p(G-G_t)+K_i \int (G-G_t)dt+K_d \frac{dG}{dt} \quad (1)$$

where G – measured value at time t, Gt – target value, Kp, Ki, Kd – the coefficients of the proportional, integral and differential parts of the controller.

The scheme of the control system with feedback of this type is presented in Fig. 1.

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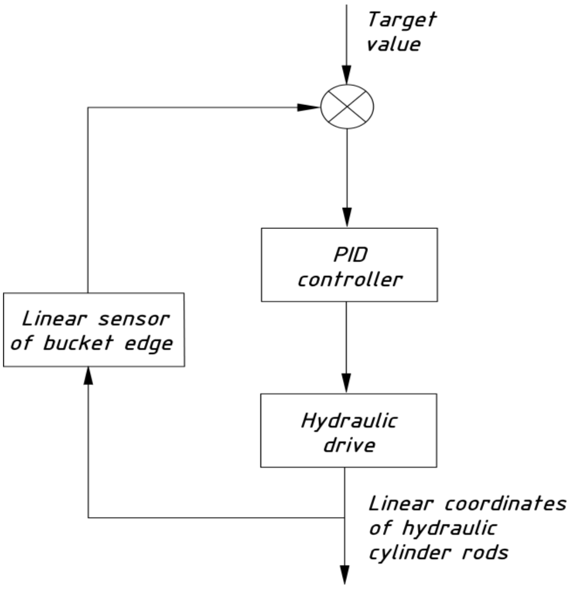

Figure 1. Feedback control

III. Development of a PID-regulation System

To control the excavator, a PID control has been introduced into the hydraulic cylinder control system. Hydraulic drives that move the rods of the hydraulic cylinders of the working mechanism affect the output coordinate - the position of the cutting edge of the working mechanism of the excavator bucket. The excavator is controlled by a volumetric hydraulic drive with a gear pump. To influence the linear coordinates of the position of the hydraulic cylinder rod, it is necessary to change the pump parameters. In this case, to transfer the necessary control action to the linear coordinates of the hydraulic cylinder rods (and hence the speed of movement of the hydraulic cylinder rods), it is necessary to influence the hydraulic cylinder flow rate.

$$v=\frac{Q}{f_p}, \quad (2)$$

where v – speed of movement of a rod of a hydraulic cylinder, Q – hydraulic flow rate, fp – piston area.

In turn, hydraulic flow rate Q depends on V – volume of gearing in the pump, n – number of cycles on T – during operation. So the final formula depending on the speed of movement of the rod of the hydraulic cylinder from the flow can be written as follows:

$$v=\frac{Q}{f_p}=\frac{V\cdot n}{T\cdot f_p}, \quad (3)$$

In turn, the number of cycles n depends on the number of turnovers n_t and the number of gear teeth z:

$$n=n_t\cdot z, \quad (4)$$

For ω angular velocity of the gear spindle:

$$n=2\pi\cdot\omega\cdot z, \quad (5)$$

Thus, it is possible to obtain the transfer function from the gear motor to the hydraulic cylinder:

$$v=\frac{V\cdot 2\pi\cdot\omega\cdot z}{T\cdot f_p}, \quad (6)$$

So, in order to influence the linear coordinate of the movement of the hydraulic cylinder rod, it is necessary to change the angular speed of rotation of the pump gear. There is a direct relationship between the flow rate of the hydraulic drive Q and the angular transmission speed ω. The greater the value ω of the angular speed of transmission, the greater the value Q of the flow rate of the hydraulic drive.

To adjust the speed of the hydraulic cylinder, it is necessary to influence three parameters:

- Angle φ;
- Angular velocity ω;
- Angular acceleration ε.

In a PID controller, each component has its own effect:

- The proportional component (P) affects the angular velocity ω;
- The integral component (I) affects the angular coordinate φ;
- The differential component (D) affects the angular acceleration ε.

Thus, for the PID-controller, all three values for the hydraulic drive are obtained: with what angular speeds and accelerations the hydraulic drive should work and at what angle it should turn. In these calculations, all the kinematic parameters of the hydraulic drive motor are known.

The implementation of PID control is based on the ratio of the measured and target functions. The PID controller is calculated so that the measured function is converted to an objective function, as shown in Fig. 2. The measured value as a result of the PID control should tend to the desired (target) position of the excavator bucket cutting edge.

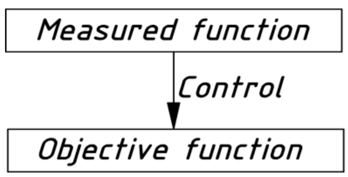

Figure 2. Scheme of the PID- regulator

IV. Problems of Introducting PID-regulation

However, during excavation works performed by a single-bucket excavator, the digging process proceeds quickly, the working conditions are unknown. The introduction of PID control for the measured current coordinate is impractical because it is entered into the next measurement. Thus, with the introduction of PID control in excavators, the predicted function replaces the measured function - the calculated coordinate of the next point of the cutting edge (Fig. 3).

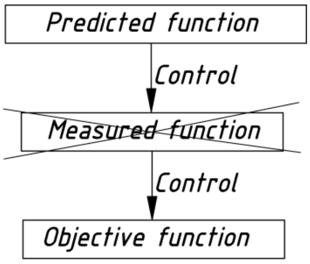

Figure 3. Required PID-regulator circuit

PID-regulator are substituted for predicted and measured by previous cycles.

V. Application of PID-Regulators to an Excavator Model

The control system of the excavator working mechanism is very difficult to set up. Adjustment of the control system is hampered by the operating conditions of excavators and environmental conditions, incomplete information about the dynamics of machines and the complexity of modeling the processes of earthworks. Finding the best solution to such a design problem requires collecting data on the design of various mechanical systems and taking into account the complexity of their work and the methodology for constructing various mathematical models [10-17]. When adjusting the control system manually (taking into account the operating experience), there is no guarantee of satisfactory operation of the built-in control system [18-21].

For calculations we chose the Russian crawler excavator CHETRA EGP-230 with the "backhoe" equipment (Fig. 4) produced by "CHETRA–Industrial machines" (Cheboksary).

Figure 4. Single-bucket r excavator CHETRA EGP-230

Calculation of positions was held with usage of mathematical model of mechanism kinematics [9, 21]. Graphical representation of kinematical model is shown on Fig. 5.

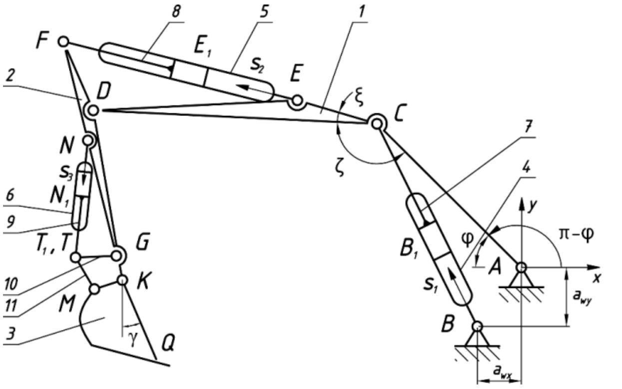

Figure 5. Kinematic scheme of the working mechanism, where 1 – boom; 2 — handle; 3 — bucket; 4, 5, 6 — cylinders; 7, 8, 9 — valve cylinders; 10 — rocker; 11 — thrust

The position of the cutting edge of the excavator bucket can be described by the function f=f(s_1, s_2, s_3) of the generalized coordinates of the input action, where s_1, s_2, s_3 – linear coordinates characterizing the displacement of the rods of hydraulic cylinders [2,8,9].

Thus, the kinematic diagram of the flat working mechanism of the excavator with the number of mobilities W = 3 has three generalized coordinates of the input action and three coordinates of the output action and can be conditionally represented as a connected control system (Fig. 6).

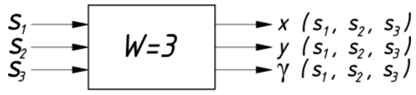

Figure 6. Conditional representation of the scheme of the working mechanism of the excavator

The mathematical model of the kinematic diagram of the excavator working mechanism is built in the MATLAB system, described in detail in [8]. This model allows:

- Investigate the characteristics of the kinematic chain of the working mechanism of a shovel excavator;
- Assess the impact of each of the chain links on the work area and service area;
- To assess the accuracy of the position of the cutting edge of the bucket 3 depending on the input generalized coordinates.

On the model of the kinematic chain of the working mechanism, the accuracy of the dimensional chain was analyzed, taking into account possible errors in the manufacture of all links and assembly units within the tolerance field. The specified study of the supplemented mathematical model of the working mechanism is described in [8, 9].

The mathematical model of the excavator working mechanism should take into account:

- Error in the manufacture of links;
- Transmission influence;
- Unevenness of the soil;

- Dynamics of the working mechanism;
- Signal delay;
- Temperature change in the lengths of the links;
- Clearances in kinematic pairs; and many other factors.

For the analysis and verification of the introduced regulation, a large-scale model of the working mechanism of the excavator was created on the basis of the training intellectual robotic center.

For a given initial sequence diagram of an ideal workflow (Fig. 7), an algorithm is defined for changing all the generalized coordinates.

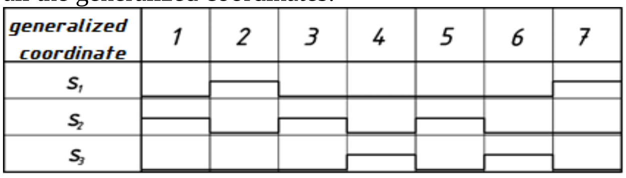

Figure 7. Workflow sequence diagram

For this experiment, the values of the generalized coordinates are changed to the following values:

- s_1 = 600 mm;
- s_2 = 200 mm;
- s_3 = 300 mm.

All values have a plus sign. This replacement was introduced for the convenience of working with the working mechanism model and removing from it the positions of the cutting edge of the bucket along the vertical axis above the support plane of the working mechanism model.

The positions of the bucket cutting edge on the x-axis are not fixed, since this does not affect the accuracy of forming the longitudinal profile of the trench bottom.

This experiment was repeated 30 times to average the results and improve the reliability of the conclusions.

The results of measuring the position of the cutting edge of the bucket model are given in Table I. The table is similar to the diagram of the working mechanism in Fig. 5 for convenience, the designation of the Q point on the cutting edge of the excavator bucket.

The ideal position of the Q point of the cutting edge of the bucket of the excavator working model calculated by the program is 215.1 mm above the support plane of the excavator working mechanism model, if all errors were absent and the mechanism would work perfectly.

TABLE I. THE RESULTS OF MEASUREMENTS OF THE POSITION OF THE CUTTING EDGE OF THE BUCKET MODEL OF THE WORKING MECHANISM OF THE EXCAVATOR

№	Position of point Q, mm		№	Position of point Q, mm
1	175.9		16	201.4
2	142.3		17	205.3
3	159.2		18	217.7
4	182.2		19	198.9
5	198.9		20	208.6
6	172.4		21	209.5
7	201.6		22	212.3
8	204.4		23	198.9
9	188.3		24	215.6
10	214.1		25	215.0
11	212.3		26	221.9
12	198.1		27	205.9
13	167.0		28	215.6
14	191.9		29	225.6
15	195.4		30	232,6

The results of multiple measurements of the cutting edge of the bucket model of the excavator's working mechanism and the ideal position of the bucket cutting edge of the excavator's working mechanism model in case all errors were absent, as well as the limits of the SNiP tolerance field for clarity, are presented graphically in Fig. 8.

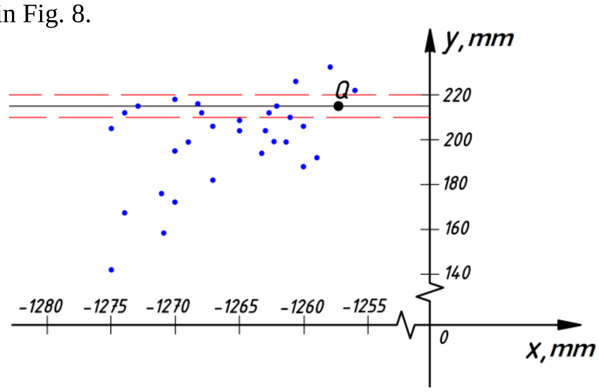

Figure 8. The position of the cutting edge of the bucket is ideal and based on the results of 30 measurements for the model of the working mechanism

As can be seen from Fig. 7, the positions of the Q points on the bucket cutting edge of the excavator's working mechanism model are very different from the calculated ideal position.

If adjustments are made by the PID-controller, multiple measurements of the bucket cutting edge of the working mechanism model are also performed to compare them with the results without adjustments presented in Fig. 8.

The results of multiple measurements of the cutting edge of the bucket cutting edge of the working mechanism of the excavator are shown in the table II in 30 measurements and in Fig. 9.

TABLE II. THE RESULTS OF MULTIPLE MEASUREMENTS OF THE CUTTING EDGE OF THE BUCKET MODEL OF THE WORKING MECHANISM OF THE EXCAVATOR WITH THE INTRODUCTION OF PID-CONTROL

№	Position of point Q, mm			№	Position of point Q, mm	
	Baseline value	Value after the PID-controller			Baseline value	Value after the PID-controller
1	175.9	175.9		16	201.4	210.6
2	142.3	142.3		17	205.3	210.7
3	159.2	159.2		18	217.7	210.4
4	182.2	215.8		19	198.9	210.7
5	198.9	216.0		20	208.6	210.4
6	172.4	212.3		21	209.5	210.4
7	201.6	210.1		22	212.3	210.5

8	204.4	210.4		23	198.9	210.1
9	188.3	210.8		24	215.6	210.8
10	214.1	210.4		25	215.0	210.4
11	212.3	210.5		26	221.9	210.7
12	198.1	210.9		27	205.9	210.4
13	167.0	210.4		28	215.6	211.0
14	191.9	210.8		29	225.6	210.6
15	195.4	210.3		30	232.6	210.4

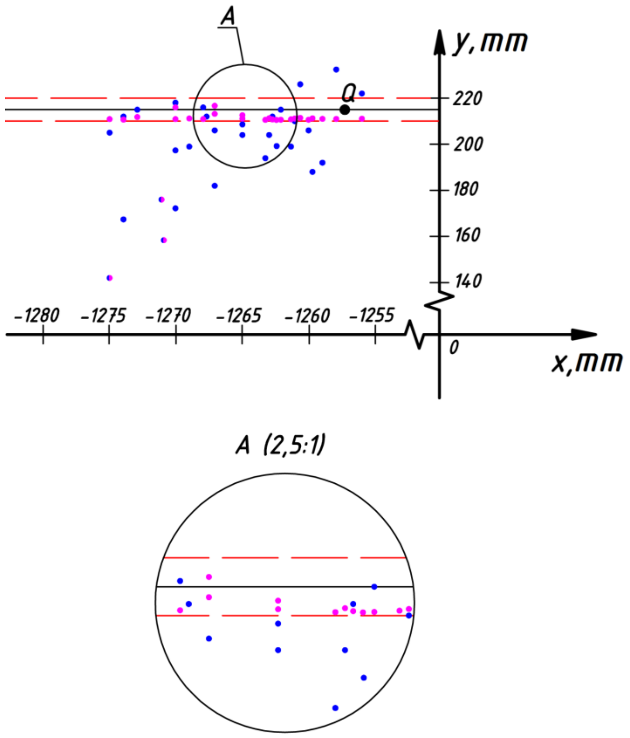

Figure 9. The results of multiple measurements of the cutting edge of the bucket model of the working mechanism of the excavator with the introduction of the PID-controller

As shown in Fig. 9, it can be concluded that the resulting positions of the cutting edge of the bucket of the excavator's working mechanism model resulting from the adjustments of the PID-controller are inside the tolerance field. The adjustments made it possible to significantly reduce the range of oscillations and bring the position of the cutting edge of the bucket to the model of the working mechanism of the excavator to the desired value - the ideal position of the cutting edge.

VI. Discussion

This method of PID control allows you to control the position of the bucket cutting edge, keeping it within specified limits. Often, when digging in unknown conditions (unpredictable soil change, heterogeneous soil, inclusions, cultural layer), the bucket cutting edge can go beyond the specified limits. At the same time, the deepening of the bucket is unacceptable because the pipes must be laid on the ground of an undisturbed structure.

This correction method is designed so that the position of the cutting edge is not worse than it would be without the correction. That is, if, according to calculations, it turns out that it cannot be done better, then the program includes inaction at this step, but the process does not deteriorate. Thus, you can solve the problem of digging the bucket below the minimum value, which is unacceptable according to the laws of Russia.

The proposed method for adjusting the position of the cutting edge of the bucket based on PID controllers can be used for more accurate positioning of the cutting edge, which will lead to more accurate digging in construction and road works.

VII. Conclusion

The conducted research helps to find possible ways to solve the problem of inaccuracy of the position of the cutting edge of a shovel bucket. This problem is especially relevant when carrying out road and construction work because, according to the laws of Russia, it is allowed to lay communications on the ground of an undisturbed structure, in other words, the deepening of the cutting edge of the excavator bucket should not be allowed.

Similar problems are encountered in different areas of applied science, the most common way to solve the problem is to make adjustments based on mathematical calculation models. However, it is impossible to make changes to the construction of the excavator at this stage, therefore it is proposed to add a PID controller with a separate device. However, as noted, the probabilistic law of distribution of the measured quantity is almost always unknown in practice, therefore, an adaptive system for making adjustments was selected, the effectiveness of which for different distribution laws of the measured quantity was previously investigated.

A mathematical model of an excavator was compiled, a cyclogram of the working process was set, and a scale model of the working mechanism was assembled. The PID control system was tested on a scale model. Based on the presented results of the conducted research, one can draw conclusions:

- The constructed model of the PID controller allows to increase the accuracy of work performed by a single-bucket excavator;
- If it is impossible to calculate values that would increase the accuracy of the work, it is possible not to worsen the digging process;
- Requirements for the management system have been formed.

Conflict of Interest

The author declares no conflict of interest.

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Mrs. Arina D. Terenteva won competition as the best tutor of Bauman Moscow State Technical University in 2016/2017 year. Also, in 2018, Arina D. Terenteva won the Golden Names of Higher School project, an annual competitive selection on the recommendation of universities and research institutions of the Russian Federation.