Investigation of the Positioning Accuracy of the Manipulator Working Mechanism

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***Abstract*— The problem of the positioning accuracy of the kinematic chain elements exists in mechanisms with open kinematic chains. The coordinates of the output link must be determined precisely. If the coordinates of the output link are determined exactly, then the required movement will be specified exactly, which means that the required functions of the mechanism will be performed. This article discusses a typical open chain manipulator mechanism. This mechanism is very common and has a fairly simple scheme, you can clearly show the principles of calculation and accuracy assessment.**

***Index Terms*— manipulator, working mechanism, automatic control system, accuracy**

I. Introduction

The problem of the positioning accuracy of the kinematic chain elements exists in mechanisms with open kinematic chains [1-6]. It can be any mechanism: robot, manipulator, crane, road or construction equipment, mechanisms based on flexible tubular elements. The coordinates of the output link must be determined precisely. If the coordinates of the output link are determined exactly, then the required movement will be specified exactly, which means that the required functions of the mechanism will be performed. Otherwise, it is impossible to correctly perform the required function of the machine in question.

We will consider a typical open-chain manipulator mechanism. This mechanism is very common and has a fairly simple scheme. So we can clearly show the principles of calculating and assessing accuracy.

II. Used Manipulator Model

The working mechanism of any manipulator is an open kinematic chain. This kinematic chain is the basis of many manipulators and road and construction equipment, such as a shovel excavator. Using the example of the most typical kinematic chain, you can consider typical dependencies and transfer them to other manipulators.

A schematic diagram of the manipulator (equivalent to the working mechanism of an excavator) with characteristic points is shown in Fig. 1.

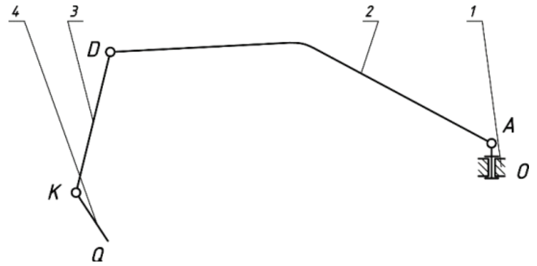

Figure 1. Schematic diagram of the manipulator, equivalent to the working mechanism of an excavator, where 1 - turntable, 2 - boom, 3 - handle, 4 - bucket

The working mechanism of a single-bucket excavator is an open kinematic chain, the kinematic diagram of the excavator working mechanism is shown in Fig. 2.

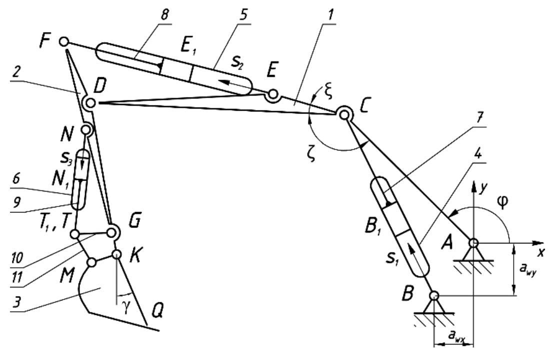

Figure 2. Kinematical model of power shovel actuator. 1 – boom, 2 – handle, 3 – bucket, 4,5,6,- hydraulic cylinders, 7, 8, 9 – hydraulic cylinders rods, 10 – rocker, 11 – thrust

The working mechanism is a flat model. The position of the working mechanism are characterized only by the coordinates along the x and y axes.

The rotation of the turntable around the vertical axis for solving this problem is not considered, because the digging process is carried out by a flat working mechanism, pre-installed in the working position. 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.

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The mathematical model of the kinematic diagram of the excavator working mechanism is built in the MATLAB system, described in detail in [1,2, 7].

The kinematic chains of other manipulators may not be a flat model, however, the output link makes the last precise movement with the manipulator's brush, performing the required technological operation, already in one plane. In this case, it can be assumed that the conclusions obtained in this study will be valid for other manipulators.

III. Analysis of the Accuracy of the Investigated Kinematic Chain

On the model of the kinematic chain of the working mechanism, an analysis of the accuracy of the dimensional chain is carried out, 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 [7]. This study is not the purpose of this work and is not presented here in detail.

As a result of the previous study, the distribution of possible errors in the service area was obtained depending on the position of the point *Q* of the cutting edge of the bucket 3 of the excavator working mechanism. The distribution of errors is calculated taking into account the errors of the stroke of the hydraulic cylinders of the working mechanism for idealized links without taking into account the errors of their manufacture. The distribution of possible errors is shown in Fig. 3. For clarity, the figure also shows the ground line, taking into account the height of the tracked base.

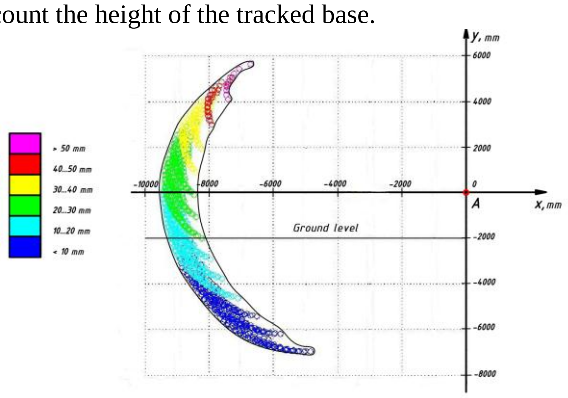

Figure 3. The distribution of possible errors of the position of point Q in the service area

Fig. 3 shows that when work is carried out above the ground level, the error in the position of the cutting edge takes on a value of 10 mm or more, while the SNiP (Stroitel'nye normy i pravila - building norms and rules) existing in Russia [7] allow soil shortages at the base earthworks developed by excavators, as well as during the construction of closed pipelines and water supply and sewerage facilities 0.05 m.

Only this deviation can lead to the bucket cutting edge going out of the required tolerance range. But the calculated deviation includes only one factor, and does not take into account: influence of transmission; 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.

That is, the compliance of all links with the requirements does not guarantee compliance with the required accuracy of movement of the output link of the kinematic chain. To improve the accuracy of the position of the cutting edge in the service area, it is necessary to select a rational method of controlling the working mechanism, which ensures the required accuracy of work.

IV. Methodic of Adjustment in Positioning System

The technique should be effective, the technique should not make changes in the design of the working mechanism, because it is not advisable in a practical task.

However, the working mechanism of the excavator operates under rapidly changing and notoriously unknown conditions. These circumstances make it difficult to design and configure workflow management systems. Most of the parameters are manually changed by the excavator operator based on years of experience. Such manual adjustment does not guarantee the quality of the control systems.

The adaptive control system can take into account changes in external conditions and machine parameters. But any system must be checked for operability and adequacy, because when replacing a real process with a mathematical model, it is possible to obtain a methodological error. In this case, the digging process may become unmanageable and adjustments to the control system may impair the result. The correction system adjusts the applied hydraulic actions, which leads to a more accurate position of the cutting edge of the implement within the tolerance band based on the positions of the cutting edge.

In previous works [8-11] on this topic, effective management of the moving average is shown. Such control takes into account the trend of changes in the parameters of the external environment and can be corrected in the process of changing conditions.

Evaluation of the efficiency of the introduced corrections is determined by the coefficient of increasing the accuracy ψ_T, which is the ratio of the standard deviation of the digging accuracy after the introduction of corrections to the standard deviation of the process before the introduction of the corrections:

$$\psi_T = \frac{\sigma_C}{\sigma}, \tag{1}$$

With the introduction of such a coefficient of increasing accuracy, the control efficiency is determined by $\psi_T < 1$.

The next formulas for adjustments are examined:

1 $k_1 \cdot \overline{x_i}$

2 $k_1 \cdot \overline{x_{i-1}} + k_2 \cdot \left(\overline{x_{i-1}} + \overline{x_i}\right)$

3 $k_1 \cdot \overline{x_{i-1}} + k_2 \cdot \left(\overline{x_{i-1}} + \left(\overline{x_i} + k_1 \cdot \overline{x_{i-1}}\right)\right)$

$$4\ k_1 \cdot \left(\overline{x_i} - \overline{x_{i-1}}\right) \quad (2)$$
$$5\ k_1 \cdot \overline{x_{i-2}} + k_2 \cdot \left(\overline{x_{i-2}} - \overline{x_{i-1}}\right) + k_3 \cdot \left(\overline{x_i} - \overline{x_{i-1}} - \overline{x_{i-2}}\right)$$
$$6\ k_1 \cdot \left(\overline{x_i} - \overline{x_{i-1}}\right) + k_2 \cdot \left(\overline{x_i} - \overline{x_{i-1}}\right)^2$$
$$7\ k_1 \cdot \left(\overline{x_i} - \overline{x_{i-1}}\right) + k_2 \cdot \left(\overline{x_i} - \overline{x_{i-1}}\right)^2 + k_3 \cdot \left(\overline{x_i} - \overline{x_{i-1}}\right)^3$$

where $\overline{x_i}$ – moving average on step i; $\overline{x_{i-1}}$ – moving average on step (i-1); k_i – correction coefficient.

The calculation methodology is based on the calculation of the moving average for the last three values. The solution to the problem consists in choosing the values k_1, k_2, k_3, selected in such a way that the coefficient ψ_T was minimal. If it is impossible to introduce corrections that improve the process (ψ_T <1), then a decision is made not to make adjustments at this control step so as not to worsen the process (ψ_T = 1).

For each formula, the minimum required number of values is determined, according to which the first adjusted value can be calculated, depending on the structural components of the moving average variations included in the formula. For convenience, the results are summarized in Table I.

TABLE I. THE MINIMUM REQUIRED NUMBER OF VALUES FROM WHICH THE FIRST CORRECTED VALUE CAN BE CALCULATED FOR EACH FORMULA

Formula number	1	2	3	4	5	6	7
The minimum number of values for calculations	3	4	4	4	5	4	4

For the measurement with the next serial number, the corrected value may already be calculated.

Based on the experiments carried out, it was shown that:

1 for any digging process, a non-negative result can be obtained due to the principle of inaction incorporated in the methodology, if improvement is impossible;

2 the best results can be achieved with a relatively small number of digging iterations n ⩽ 30, the efficiency for all the proposed formulas is on average ψ_T = 0.75 ... 0.85, and in some cases reaches values of ψ_T = 0.12;

3 the following formulas showed the greatest efficiency (in descending order of efficiency): 5, 2, 1, 3;

4 in the presented experiment, formulas 4, 6, 7 were ineffective in comparison with the rest of the proposed ones.

V. EVALUATING THE EFFECTIVENESS OF PREVIOUS STATISTICAL FINDINGS.

On the prototype of the working mechanism, the effectiveness of the presented statistical conclusions should be checked. Such a check will make sure that the conclusions made from a mathematical point of view are correct, and also check that the system does not become unmanageable due to the replacement of a real process with a model.

The studies are carried out in the area above the ground line, where there was a deliberately large error in the position of the cutting edge due to the movement of the hydraulic cylinder rods (Fig. 3).

At each moment in time, the positions of the cutting edge along the trajectory of movement specified by the work sequence are recorded, and at each step, adjustments to the target position are made based on several previous positions based on the moving average calculations described above.

For the experiment, one required position of the cutting edge X_T = 1075.5 mm was introduced, then, taking into account the regulated value of 50 mm, values were obtained that limit the tolerance field X_{ES} = 1100.5 mm and X_{EI} = 1050.5 mm.

On the basis of the carried out statistical study of the mathematical value, the method of measurement and processing of the experimental results is determined:

- 25 values of the cutting edge position are continuously measured;
- For each value, adjustments are made and the efficiency calculated.

The effectiveness of the introduced control will be evaluated along the boundaries of the tolerance field. Such an assessment will allow you to check whether the output link of the manipulator is within the required interval within the permissible error.

To assess the effectiveness of the introduced adjustments, an empirical criterion ϑ is introduced, which is defined as the product of multiplier criteria:

$$\vartheta = \vartheta_1 \cdot \vartheta_2 \cdot \vartheta_3 \quad (3)$$

where ϑ_1 - criterion for going beyond the upper limit; ϑ_2 - criterion for going beyond the lower limit when accumulating measurements before the introduction of adjustments; ϑ_3 - criterion for going beyond the lower boundary of the tolerance field in the corrected process.

A. Criterion for Going Beyond the Upper Bound ϑ_1

The criterion for going beyond the upper limit of the tolerance field ϑ_1 is defined as the ratio of the sum of squares of the ratio of the difference between the upper limit of the tolerance field X_{ES} and the measured values X_i to the value of the required position of the cutting edge X_T to the total number of measurements *n*:

$$\vartheta_1 = 1 - \frac{\Sigma\left(\frac{X_{ES} - X_i}{X_T}\right)^2}{n} \quad (4)$$

Two options are possible depending on the position of the bucket cutting edge relative to the upper limit of the tolerance field:

1 If the value of the difference in deviations $(X_{ES} - X_i)$ takes on a value greater than zero, then the measured value of the position of the cutting edge of the bucket does not go beyond the upper limit of the tolerance range.

2 If the value of the difference in deviation $(X_{ES} - X_i)$ is less than zero, then the measured value of the position of the cutting edge of the bucket is outside the upper limit of the tolerance range.

In the first case, when $(X_{ES} - X_i) > 0$, for calculating the criterion ϑ1 the value of the difference in deviations $(X_{ES} - X_i)$ is taken equal to zero, then the second term in the formula is zeroed, hence the criterion ϑ1 = 1. That is, the condition of this criterion is fulfilled and does not affect the empirical criterion ϑ.

In the second case, when $(X_{ES} - X_i) < 0$, to calculate the criterion ϑ1, the calculated value of the difference in deviations is taken $(X_{ES} - X_i)$ and is taken into account in the calculation of the criterion ϑ_1, which affects the empirical criterion ϑ.

When calculating adjustments using formulas 1,2,3,5, the value of the criterion for going beyond the upper limit $\vartheta_1 = 1$. Corrections for these formulas are not displayed on the graph, the calculation results for all other formulas are shown in Fig. 4.

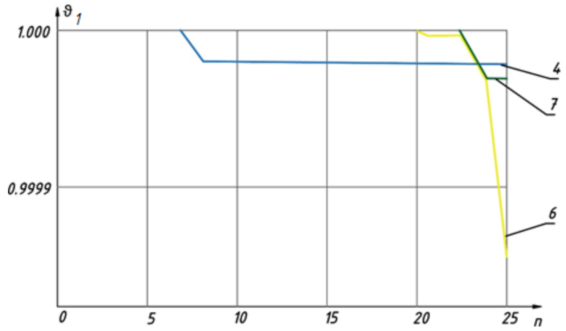

Figure 4. Distribution of the criterion for going beyond the upper bound ϑ_1 when making corrections according to the formulas

The lower the value of criterion ϑ_1, the worse the result of the introduced corrections and the faster the cutting edge can go beyond the upper limit of the tolerance range.

B. *Criterion for Going Beyond the Lower Limit before the Introduction of Adjustments ϑ_2*

The criterion for going beyond the lower limit when accumulating measurements before the introduction of adjustments ϑ_2 is defined as one plus the ratio of the sum of the product of the ratio of the difference between the lower limit of the tolerance field X_{EI} and the measured values X_i to the value of the required position of the cutting edge X_T and the inverse ratio of the difference between the number of measurements at the beginning of control input $n_{b.c}$ and the current number of measurements n_i to the number of measurements of the beginning of control $n_{b.c}$ (according to Table I) to:

$$\vartheta_2 = 1 + \frac{\sum_1^{n_{b.c}} \left(\frac{X_i - X_{EI}}{X_T}\right)^2 \cdot \frac{1}{(n_{b.c} - n_i)}}{n_{b.c}} \qquad (5)$$

This criterion ϑ_2 is calculated at the stage of running-in the correction method, that is, the minimum required number of values for each formula is taken as the number of measurements of the beginning of control input $n_{b.c}$, according to which the first corrected value can be calculated from Table I plus one. In fact, this is the serial number of the first measurement of the controlled process.

Depending on the position of the bucket cutting edge relative to the lower limit of the tolerance field, two options are possible:

1 If the value of the difference in deviations $(X_i - X_{EI})$ is less than zero, then the measured value of the position of the cutting edge of the bucket is outside the lower limit of the tolerance range.

2 If the value of the difference in deviations $(X_i - X_{EI})$ takes on a value greater than zero, then the measured value of the position of the cutting edge of the bucket does not go beyond the lower limit of the tolerance range.

In the first case, when $(X_i - X_{EI}) < 0$, the lower limit of the tolerance field occurs, this point must be taken into account in assessing the effectiveness of the introduced adjustments by the empirical criterion ϑ. To calculate the criterion ϑ_2, the calculated value of the difference in deviations $(X_i - X_{EI})$ is taken and taken into account in calculating the criterion ϑ_2, which affects the empirical criterion ϑ.

In the second case, when $(X_i - X_{EI}) > 0$, there is no exceeding the lower limit of the tolerance field, this measurement will not be taken into account. To calculate criterion ϑ_2, the value of the difference in deviations $(X_i - X_{EI})$ is taken to be zero, then the second term in the formula is zeroed, therefore criterion $\vartheta_2 = 1$. That is, the condition of this criterion ϑ_2 is fulfilled and does not affect the empirical criterion ϑ.

The results of calculating the criterion for going beyond the lower limit before the introduction of adjustments ϑ_2 are presented in Fig. 5. Moreover, the calculated values of the criterion for the introduction of adjustments according to formulas 2,3,4,6,7 coincide.

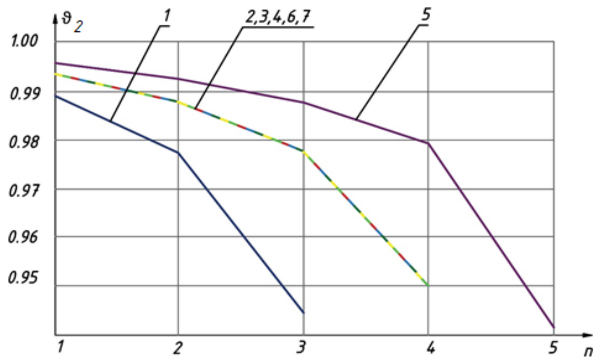

Figure 5. Distribution of the criterion for going beyond the lower boundary ϑ_2 when making corrections according to the formulas

The lower the value of criterion ϑ_2, the worse the result of the introduced corrections and the faster the cutting edge can go beyond the lower limit of the tolerance field.

C. *Criterion for Going beyond the Lower Limit in a Controlled Process ϑ_3*

The criterion for going beyond the lower boundary of the tolerance field in the controlled process ϑ_3 is determined similarly to the criterion ϑ_3, but already in the regulated process (at the stage of the excavator operation, taking into account the introduced adjustments).

$$\vartheta_3 = \frac{n}{\sum_{n_{H.y}}^{n} \left(\frac{X_i - X_{EI}}{X_T}\right) \cdot \frac{1}{(n_i - n_{b.c})}} \qquad (6)$$

where i - is the number of digging iterations in the controlled process; that is, the number i is greater than the minimum required number of measurement values for each formula from which the first corrected value can be calculated.

Due to the fact that going beyond the lower boundary of the tolerance field is unacceptable according to the current SNiP, it is all the more unacceptable in a controlled process when adjustments are made to the control system of the excavator's working mechanism, which is introduced, among other things, to prevent possible deepening of the bucket, criterion ϑ_3 will take two possible values:

1 $\vartheta_3 = 0$, if as a result of making adjustments to the control system of the excavator working mechanism in the corrected process, the cutting edge reaches the lower boundary of the tolerance field.

2 $\vartheta_3 = 1$, if, as a result of making adjustments to the control system of the excavator working mechanism in the corrected process, work occurs within the lower limit of the tolerance field.

That is, if the value of the difference in deviations $(X_{\mathrm{i}} - X_{\mathrm{EI}})<0$, then the measured value of the position of the cutting edge of the bucket goes beyond the lower limit of the tolerance field and $\vartheta_3 = 0$, and if the value $(X_{\mathrm{i}} - X_{\mathrm{EI}})> 0$, then the measured value of the position of the cutting edge of the bucket does not go beyond the lower limit of the tolerance field and $\vartheta_3 = 1$.

If the value of the criterion $\vartheta_3 = 1$, then the condition of this criterion is fulfilled and does not affect the empirical criterion ϑ. If $\vartheta_3 = 0$, then the value of the empirical criterion ϑ will immediately signal an inadmissible deepening of the bucket cutting edge.

The results of calculating the criterion for going beyond the lower limit in the controlled process ϑ_3 are an array of values 0 or 1, therefore, they are not shown graphically. The results of calculating this criterion are included in the general empirical criterion ϑ.

D. Empirical Criterion ϑ

To assess the effectiveness of the introduced adjustments, an empirical criterion ϑ was introduced, which is the product of multiplier criteria $\vartheta = \vartheta_1 \cdot \vartheta_2 \cdot \vartheta_3$.

The results of calculating the empirical criterion are shown in Fig. 6.

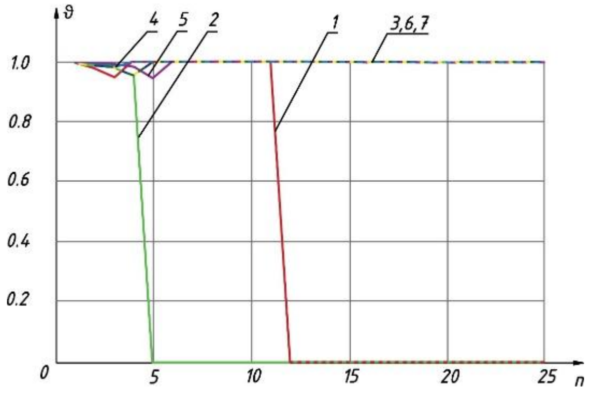

Figure 6. Distribution of empirical criterion ϑ when making adjustments for all formulas

From the graphically presented results of calculating the empirical criterion ϑ, it can be seen that making adjustments according to formulas 1 and 2 is ineffective, since the criterion $\vartheta = 0$. This result $\vartheta = 0$ indicates going beyond the lower limit in the controlled process, which, firstly, is unacceptable according to the current SNiP, and, secondly, it shows the ineffectiveness of the system for making adjustments that prevents the bucket from sinking.

The results of effective formulas for making adjustments that do not lead to zeroing of the empirical criterion ϑ are shown in Fig. 7.

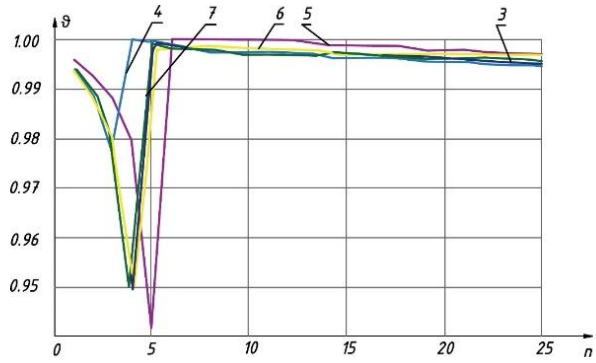

Figure 7. Distribution of the empirical criterion ϑ when making adjustments using formulas 3,4,5,6,7

From the presented results, it can be seen that in the worst case of making adjustments (formula 5) no later than n = 6 measurements, the empirical criterion $\vartheta = 1$, which indicates the effectiveness of the adjustments made, and bringing the process into a controlled state.

VI. Conclusion

The studies carried out, reflected in the figures in this article, led to the following conclusions:

1. Derived an empirical criterion for assessing the introduced control;

2. Shows the effectiveness of some formulas for the introduction of adjustments.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Eugene O. Podchasov conducted the research and analyzed the data.

Arina D. Terenteva improved the mathematical model, wrote an article.

All authors had approved the final version.

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