Precision Analysis of Earthworks Made by Power Shovel Actuator

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***Abstract*— In building industry there is a need to use high-precision construction vehicles equipped with control systems for trenching. The most promising machines equipped with a control system are based on adaptive methods so they allow you to choose the control algorithm during work processes. The need for such systems is caused by high requirements to the production of excavation work, the established construction norms and rules. A significant proportion of works on laying of communications is performed using shovel excavators with hydraulic drive. To obtain practical recommendations for improving the accuracy and application of control systems a mathematical model of working mechanism of the shovel excavator was developed. It allows us to assess the accuracy of excavation work, to identify possible sources of geometric errors and to compile a working area and a service area. It is also possible to analyse kinematic and process errors and identify their sources. Two ways to reduce error to acceptable limits with the use of a control system, and without it on existing equipment are proposed in this paper.**

***Index Terms*— shovel excavator, mathematical model, control system, service area, accuracy**

I. Introduction

In city conditions in Russia it is necessary to lay trenches for telephone and electrical networks, water supply and sanitation. Work is carried out in cramped conditions, so high-precision excavators with hydraulic drive should be used. They are capable of performing up to 38% of the excavation works. Thus, improving their technical characteristics and accuracy of working are important for machine-building enterprises, and developers of such mechanized devices [1-5].

II. Analysis of the Problems Affecting the Accuracy of the Shovel Excavators

The construction norms and rules establish high requirements to precision excavation works in Russia. Excavator-caused ground shortfalls of no more than 0.05 m are allowed [6, 7]. This high requirement is often impossible to provide for with the devices available.

The control system of an excavator is extremely important for excavation in urban environments. It allows you to quickly estimate the functioning of the machine itself and components of its subsystems and components using a computer [5, 8-9]. It is also possible to determine the position of an excavator and the trench in order to improve the accuracy of the digging process more precisely. The choice of a controlling method for earthworks should be based on its dynamic properties and statistical characteristics of random disturbances acting upon it. The main trend of automation of shovel excavators is controlling the excavator bucket in order to ensure high quality work to meet the requirements concerning geometric accuracy of the trench.

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. The aim of this paper is to analyse the precision of excavator works.

III. The Kinematic Model of the Working Mechanism of an Excavator

Modeling control systems of the working mechanism in order to enhance the precision digging of the ground is impossible without making a mathematical model of the process and working mechanism.

The accuracy of the digging mechanism has impact not only on the control accuracy that is dependent on the operator, working in manual mode, or computer-aided management including the delay in any of these options, but also on soil characteristics, surface roughness, precision components of operating mechanism such as: boom, stick, cylinders, and the errors permitted in their manufacture.

It is needed to choose an excavator model to simulate the control systems of the working mechanism to offer guaranteed methods of increasing the accuracy of trenching. They can be used for other excavators you select, however, no conclusions or recommendations for making specific decisions concerning simulation are possible without reference to a specific type.

For calculations we chose the Russian crawler excavator CHETRA EGP-230 with the "backhoe" equipment (Fig. 1) produced by "CHETRA–Industrial machines" (Cheboksary).

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Figure 1. Crawler excavator CHETRA EGP-230

The plain model of the shovel excavator's working mechanism was built on the basis of structural and kinematic relations which allows to investigate the design features of work mechanism with the number of degrees of freedom of $W = 3$ [7] (Fig. 2).

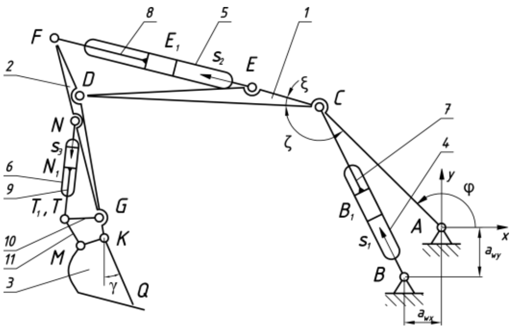


Figure 2. Kinematic diagram of the working mechanism: 1 — boom; 2 — handle; 3 — bucket; 4, 5, 6 — cylinders; 7, 8, 9 — valve cylinders; 10 — rocker; 11 — thrust

For the plain model of the excavator mechanism the coordinate inputs are s_1, s_2, s_3 and the output coordinates are x, y, γ. The kinematics of working mechanism of an excavator should be described according to the method of the projections of the vector paths. In the fixed coordinate system position of rotational kinematic pairs the operating mechanism is defined by the coordinates of the centers of the pairs. The position of the sliding pairs is determined by the coordinates of any point lying on a guide, and the angle between the positive direction vector of the pair and the x-axis. Geometric analysis of all segments of the kinematic chain of the excavator mechanism is based on the variation of the coordinates s_1, s_2, s_3 using MATLAB simulations [10-12]. Variation of the position of all kinematic chain segments of the operating mechanism of the excavator is given by position functions.

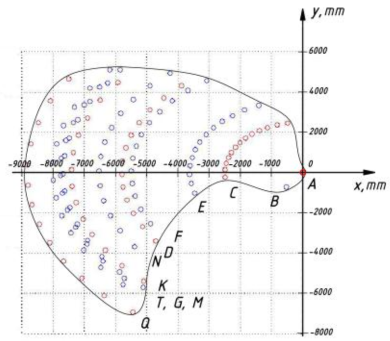
IV. Operation Areas and Service Areas of the Excavator

The mathematical model allows us to analyse the parameters of the kinematic chain of the shovel excavator's operating mechanism to measure the influence of each of the segments on the work area and service area [12], and the position precision of the cutting edge of the bucket 3 (Fig. 2) depending on the input coordinates. It is necessary to calculate the operation area to study the accuracy of the position of the bucket 3 at any point.

In order to determine the effect of the input coordinates to position of the cutting edge of the bucket 3 (Fig. 2), the operation areas of each of the input generalized coordinates were sequentially expanded. A possible displacement was introduced starting from s_1 to s_3 (Fig. 4).

The total operation area is a set of locations of the hydraulic cylinder 4 (coordinate s1). Each of them was overlaid by numerous locations of the hydraulic cylinder 5, which were, in turn, overlaid by the locations of the hydraulic cylinder 6 (see Fig. 2).

The service area of the excavator's working mechanism (Fig. 5) is obtained similarly to his operation area. Due to these reasons, the service area of a working mechanism is displayed with the simultaneous variation of all three input coordinates s_1, s_2, s_3.



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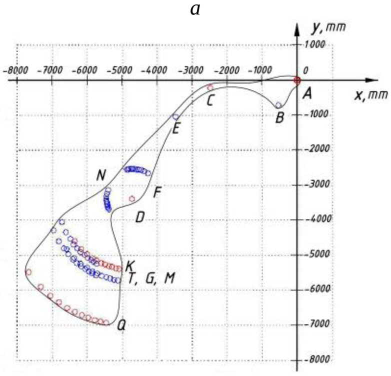

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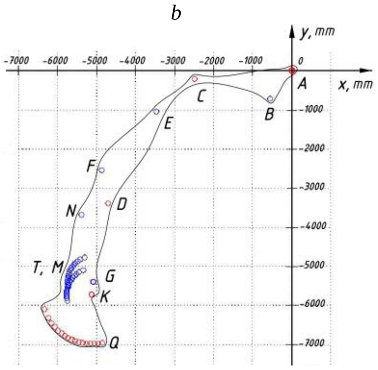

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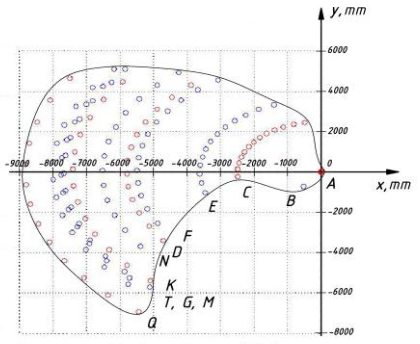
Figure 3. The dependence of the operation area excavator's mechanism on the input coordinates: *a* – $s_1 = var$, $s_2=0$, $s_3=0$; *b* – $s_1 = 0$, $s_2 = var$, $s_3=0$; *c* – $s_1 = 0$, $s_2=0$, $s_3=var$



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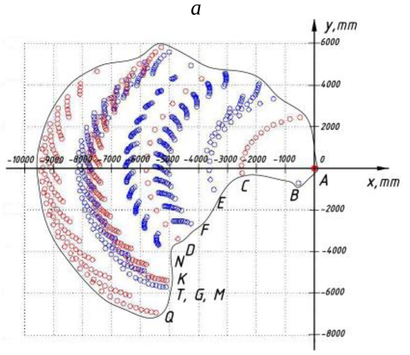

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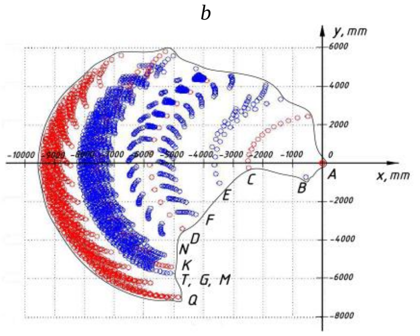

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Figure 4. The dependence of the operation area excavator's mechanism on the input coordinates: *a* – s_1 =*var*, s_2=0, s_3=0; *b* – s_1 = *var*, s_2= *var*, s_3=0; *c* – s_1 = *var*, s_2= *var*, s_3=*var*

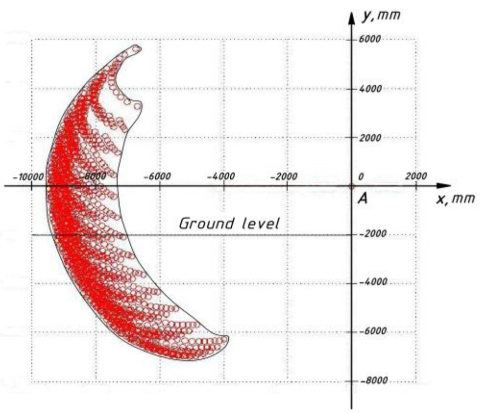

Figure 5. The dependence of the service area excavator's mechanism on a variation of the input coordinates s_1, s_2, s_3

The cumulative service area, like the operation area, is a set of positions of the point *Q* located at the bucket edge 3 (see Fig. 2). The position of the hydraulic cylinder 4 (the coordinate s_1) of the hydraulic cylinder 5 and cylinder 6 are changed sequentially.

V. Evaluation of the Geometric Errors of Movement of Excavator's Work Mechanism

All segments of the kinematic chain including the hydraulic cylinders have a manufacturing tolerance. When assembling the operating mechanism there is possibility of errors. In addition, each cylinder has a linear error displacement, depending on the length of the rod [13]. Due to manufacturing error of the boom, stick, bucket, hydraulic cylinders and assembly errors as well as other problems associated with precision control, accuracy of digging may differ significantly from the desired.

Therefore, a parametric analysis for the kinematic chain of the excavator's mechanism was performed with the dimensional chain formation. In this case, it is impossible to use standard methods of calculation of dimensional chains [14] because the kinematic chain is open.

This problem can be solved by replacing the geometric calculation by re-calculation of the kinematic chain including possible manufacturing errors and movements of the excavator's mechanism in order to determine the location of the cutting edge of the bucket.

Comparison of idealized geometric calculations (all dimensions are nominal, errors are absent) and the kinematic chain with the maximum possible linear displacement errors was performed.

The geometrical calculation of the dimension chain of the excavator's mechanism including the manufacturing errors of the elements of the operating mechanism is carried out by simulation in MATLAB. Changing the position of segments is set by position functions. Evaluation of errors of mechanism movements is performed according to the calculation of the kinematic chain (see Fig. 2) from the input segment (boom 1) to the output segment (bucket 3).

Based on the results of the calculations possible positions of the cutting edge of the bucket 3 (point *Q*) area at the time of moving into the soil at the bottom of the trench to a depth of 2.4 m considering the errors of manufacturing the segments were determined. (Fig. 6).

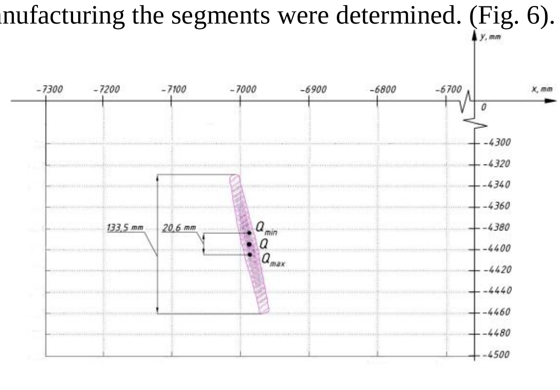

Figure 6. The area of possible positions of the cutting edge of the bucket when s_1 = 0 mm; s_2 = 300 mm; s_3 = 200 mm.

In the plotted areas for possible positions point Q is specified. This is the position of the cutting edge of the bucket 3 of the excavator at the time of moving into the soil at the bottom of the trench if all the parts of the kinematic chains are made without errors. There are also points Q_{max} and Q_{min} marked in the region. They show the position of the cutting edge of the bucket for analysis of the accuracy of possible errors using the method of maximum-minimum. Point Q_{max} is obtained with the maximum tolerance of all the segments of the kinematic chain. Point Q_{min} is obtained with undertolerance.

While performing the accuracy analysis by the method of maximum-minimum the area of possible positions is 4.7 mm along the *x*-axis and 20.6 mm along the *y*-axis, the required value being equal to 0.05 m.

Additionally, in the area of possible positions of point Q at the cutting edge of the bucket 3 the calculation of possible positions (in making all the segments of the kinematic chain without errors, the occurrence of which in the process of excavator's work is not possible) was introduced including the geometric errors in the movement of the rod of the hydraulic cylinder. In this case, the area of possible positions will significantly increase and will reach up to 57.1 mm along the *x*-axis and 133.5 mm along the *y*-axis. That is several times higher than the 0.05 m requirement.

In the case of trigonometric nonlinear open-loop kinematic chain the classic method of maximum/minimum would not give the evaluation of that combination of errors in the segments manufacture, when the error of the bucket 3 movements would be maximum. It is important to evaluate the accuracy requirements for the production of the working mechanism's segments. This error, which is systematic, is determined for each individual excavator during the acceptance tests. This error must be corrected using the control systems of the excavator, however, we should represent its possible values.

VI. Evaluation of Errors in Movement of the Excavator's Mechanism Considering the Error Displacement of the Valve Cylinders

The valve cylinders have a tolerance on the rod's movement depending on the general size. Therefore, a distribution of possible errors within the service area depending on the position of the point Q of the cutting edge of the bucket 3 of the excavator's mechanism was calculated (Fig. 7). In the calculation, we counted the error of the rod's movements for the idealized parts without including the errors of their manufacture.

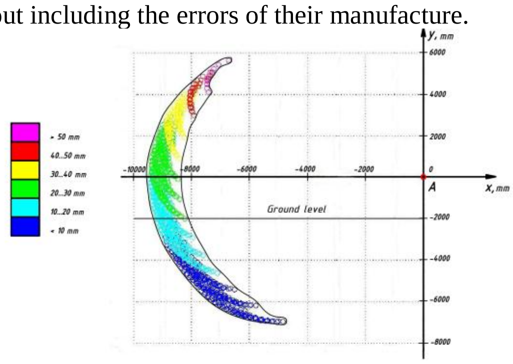

Figure 7. The distribution of possible errors of the position of point Q in the service area

Variations of the position of hydraulic cylinder rods has a significant impact on the error of position of point Q of the cutting edge of the bucket 3 of the excavator's mechanism and can be varied considerably (see Fig. 7). For clarity, in Fig. 7 there is also a line of ground surface for the specifically selected excavator with the height of the caterpillar.

VII. Conclusion

According to the results of the mathematical modeling of the excavator's mechanism we formed an area in which the cutting surface of its bucket in a variety of manufacturing errors of all its elements can occur. The area of possible cutting edge placements was investigated in the range of errors of the valve cylinders from the maximum to the minimum without including the lag. Research shows that in the case of trigonometric nonlinear open kinematic chain classic method of maximum-minimum would not give such evaluation of cylinders error combinations, when error of the output segment would be the maximum. It is important to get it to meet the accuracy requirements for manufacturing the mechanism's elements. This means that all the parts' meeting the technical requirements does not guarantee keeping the required accuracy of the movement of the output segment of the kinematic chain. Therefore, the underbreak in the base of the trench may exceed the required value, equal to 0.05 m.

One method of reducing errors is to organise the work of the excavator in the part of service area with less errors, and to perform the control algorithm organizing the output segment's work. If one needs to work in other parts of the zone, it is necessary to include the adaptive control, which will significantly reduce the variance of the resulting error of the displacement of the output segment of the excavator.

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