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EXPERIMENTAL EVALUATION OF PATH ACCURACY OF HYDRUALIC EXCAVATOR FIXTURE

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The paper provided experimental evaluation of the accuracy of programmed operational motions of the fixture of a single-bucket hydraulic excavator which was regarded as an automated earth-mover. The methodology of experimental investigations carried out at a K-111 excavator fixture stand was discussed and the obtained results were presented.

1. Introduction

To work the ground by means of an earth-mover, its cutting tool must be driven along the appropriate path, at the appropriate time. In traditional machines operational motions of the fixture are controlled by an operator. In automated machines those functions would be taken over, to a certain extent, by a control system. Such machines could not be controlled by simply applying some solutions used in robotics.

A fully automated earth-mover would correspond to a robot of 3rd generation, while robots of this kind are not used in industrial applications as yet [2]. Consequently, the systems for the automation of fittings operation are going to be introduced as the operator support arrangements, but they are not meant to replace him in the medium breaking process [1]. Therefore, the machine will be controlled by the operator while the applied systems will enable him to control the machine more efficiently, reducing his manual and intellectual effort.

Automatic control of operational motions of the fixture requires control arrangements of the necessary positions of hydraulic cylinders to be used. The changes of cylinder lengths within a certain time period determine the tool trajectory. The necessary feedback signals could be obtained in the following manner:

- directly from the position of a cutting tool,
- from the position of driving elements or fittings.

Due to technical difficulties, it proves to be more practical to use the second of the above-mentioned methods.

One of important issues related to the practical application of the control system is that it is possible to obtain high accuracy of the performance of the preset tool path. The accuracy depends on many factors, out of which the following seem to be the most important:

- the method of receiving feedback signals for control systems,
- the accuracy of measurement paths of feedback signals,
- the accepted way of planning the cutting tool path,
- the quality of control systems being used,
- the possibility of accurate specification of fixture dimensions,
- the possibility of identification of the fixture dynamic model,
- the effect produced on the machine by the medium being broken.

In fixture control systems which are possible to be used in present-day earth-movers, the factors specified above could be taken into account only to a limited extent. It is practicable to obtain data on the cutting tool position in an indirect way by measuring hydraulic cylinder lengths or fixture position angles and then to solve a simple kinematic problem. The fixture dynamic model can also be used in a limited way while planning the path and narrow-ranged fixture drive adjustment. This results from both the model complexity and the limited computing capabilities of controllers which may be used in today earth-movers.

Due to the required digital transfer band of the control system, the sampling period should range between 10 and 20 ms. Therefore, even if the fixture controller has the computing power of a PC 486 computer, the procedures of control signals and output signals development must be relatively simple. Consequently, that is related to the obtainable accuracy of a planned path.

Investigations on the planned path performance accuracy may be carried out by both the experimental and analytical methods. The results of experimental investigations carried out with a K-111 single-bucket hydraulic excavator are presented below.

2. Purpose and method of experimental investigations

At the Kielce branch of the Polish Academy of Sciences, the digital control system of a single-bucket hydraulic excavator was developed. The system has been used for research applications. Excavator motion control was achieved by means of the hydraulic cylinder position adjustment or fixture angle position adjustment. The system was developed using a PC 486 computer with A/C and C/A cards. For the sake of investigations, a stand with K-111 excavator fixture, controlled by proportional hydraulic valves and supplied from a station with a multi-piston variable capacity pump [3], was employed. Time sequences of generalized coordinates developed by the system became time-synchronized control signals for three control systems when performing the planned path. PID digital controllers or status controllers, including those with status monitors, were used in the control systems [4].

The investigations were aimed at defining the accuracy of performance of the planned excavator cutting tool path while breaking the discrete medium, with the use of a simple algorithm for path planning and hydraulic cylinder position adjustment. The choice of the medium resulted from the technical possibilities. Dolomite grit of 10 to 12.8 mm fraction was selected as the broken medium. A $1.5 \times 2.75 \times 1.2$ m (width $\times$ length $\times$ depth) excavation was filled with the medium. The investigations were conducted with a horizontal medium surcharge corresponding to the coordinate $y = -0.39$ m in the assumed Cartesian coordinate system, with the origin located in the outrigger axis of rotation.

The cutting tool location was defined indirectly by measuring the hydraulic cylinder lengths and solving a simple problem of fixture kinematics. Under such conditions, the defined path performance accuracy depended mainly on the control system quality and on the accepted method of programming of fixture motion. That allowed to obtain the above-mentioned purpose of investigations.

The quality of the planned path performance was evaluated using indices which referred to the hydraulic cylinder lengths, cutting tool coordinates and excavation field. The performance accuracy of the preset changes in fixture hydraulic cylinder lengths was evaluated by means of the following indices:

$$I_{lk} = \frac{1}{n}\sum_{i=1}^{n} |l_{ui} - l_i|, \tag{1}$$

where n – number of measurements taken for successive sampling moments, k – designation of fixture hydraulic cylinder; w – hydraulic cylinder outrigger, r – arm, and l – bucket, l_{ui} – preset length of the corresponding fixture hydraulic cylinder, l_i – actual length of the corresponding fixture hydraulic cylinder in a given stroke of system operation.

The investigations were conducted for sampling time $T_p = 10$ ms thus, with low cutting tool velocities, it was possible to compare the hydraulic cylinders lengths accurately.

The accuracy of the planned path performance was evaluated on the basis of the accuracy parameter:

$$(2) \qquad I_{xy} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_{ui}-x_i)^2+(y_{ui}-y_i)^2}\,,$$

where x_{ui}, y_{ui} – cutting tool coordinates calculated on the basis of the preset lengths of hydraulic cylinders for a given stroke; x_i, y_i – cutting tool coordinates calculated on the basis of the actual lengths of hydraulic cylinders for a given stroke of system operation.

Therefore, indices (1) and (2) defined the average deviation of hydraulic cylinders lengths and cutting tool path from their preset performances.

Moreover, the maximum values of index (2) (denoted $I_{xy\mathrm{Max}}$) as well as horizontal and vertical deviations were calculated as follows:

$$(3) \qquad \begin{aligned} I_{x\mathrm{Max}} &= \max(x_{ui}-x_u),\\ I_{y\mathrm{Max}} &= \max(y_{ui}-y_u). \end{aligned}$$

In order to evaluate the compatibility of excavation fields, the areas between a surcharge line and preset path (denoted S_u), and a surcharge line and cutting tool actual path (denoted S) were defined, and then the relative percentage difference was calculated according to the formula:

$$(4) \qquad \Delta S = \frac{|S_u - S|}{S_u} \times 100\%\,.$$

In the figures to be found below, that value was denoted by $\%S_u$.

In the investigations, the selected path of the cutting tool was planned and performed under various conditions at the research stand. Those conditions were related to:

- performance of the operation motions "in the air" and at breaking the medium,
- changes of hydraulic supply pressure and supplier capacity,
- changes of controller parameters in the hydraulic cylinder control systems.

The evaluation of quality of the planned paths performance was carried out on the basis of the indices (1 to 5).

3. Investigation results and evaluation

The investigations were carried out for the selected cutting tool paths planned by means of a point-by-point method [3, 4]. In this method planning takes place in the configuration space of the machine with linear path interpolation between intermediate points [5].

Time parametrization of the tool path was carried out basing on the assumed hydraulic supplier capacity, while setting the parameters of control signals for hydraulic cylinders fixture positions control systems was carried out in the real time.

In the control systems of hydraulic cylinder positions, digital PI controllers of the stationary algorithm were used. Controllers settings were defined according to the direct error response features for peak noises with overshoot factor $\chi = 15 - 20\%$ and the minimum setting time. Due to nonlinearity of the controlled systems resulting from alterations of the mass center of the fixture elements, together with the changes in fixture configurations, controllers settings were averaged on the basis of the values obtained from selected fittings configurations. An example of a response sequence for the arm was shown in Fig. 1. The correctness of control systems operation of hydraulic cylinders positions was reported for the specified digital controllers settings. The settings were presented in Fig. 1 a.

To present the obtained results, 4 examples of cutting tool paths were selected. They were shown in Figs. 2, 8, 10 and 11. Nodal points introduced in the course of path planning could be noticed in the figures. The paths no. 1, 2 and 4 were planned to achieve full excavator bucket filling with diggings. Path no. 3 was planned to achieve the rectilinear motion. In that case the linear interpolation used in path planning within fixture configuration space caused the necessity of defining several intermediate points in a horizontal segment.

In the experiments, the planned paths were executed at the research stand and the quality indices determined by the formulas (1)–(4) were defined. The experiment results were presented in Table 1.

The experiments were carried out under the following conditions:

1. When breaking the aggregate, with the use of controllers set as shown in Fig. 1 a and the hydraulic system supply pressure $p_z = 10$ MPa. Such conditions were in force for experiments no. 1, 7, 12 and 18.

2. When the fittings were in motion with no load from medium reaction forces, and the other conditions were as stated above – experiment no. 2.

3. When breaking the aggregate, with the use of controllers of settings as in Fig. 9.1 a, and the supply pressure increased to $p_z = 16$ MPa – experiments no. 3, 8, 14 and 19.

4. When breaking the aggregate, with the use of controllers of settings as stated above, and the supply pressure reduced to 5 MPa. Under such conditions experiments no. 4, 9, 15 and 20 were carried out.

5. When breaking the aggregate, with the use of settings as above, and the supply pressure $p_z = 10$ MPa and increased supplier capacity – experiments

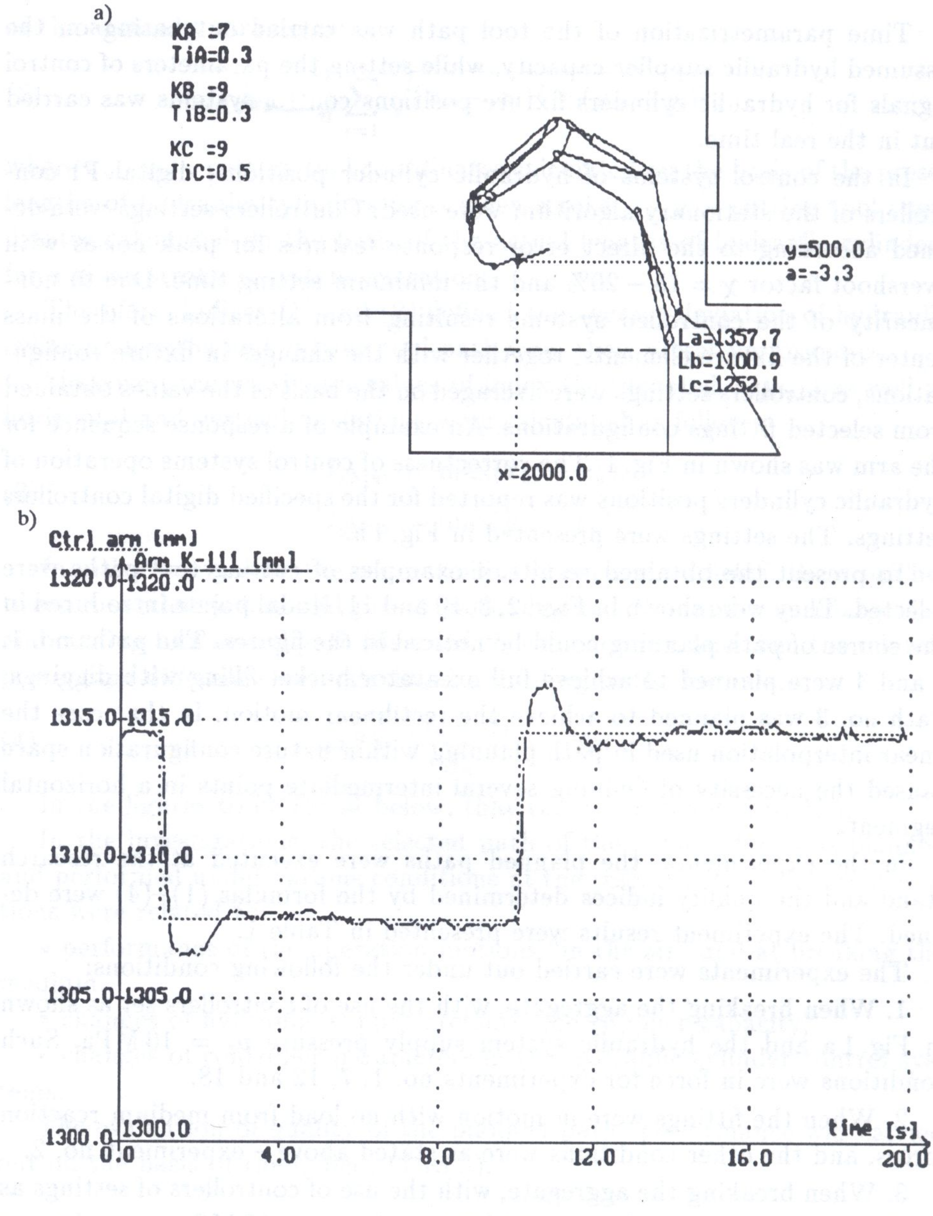

FIG. 1. Response of control system of the hydraulic cylinder arm position to a peak noise; a) fixture configuration, b) response sequence.

no. 3, 8, 14 and 19. The capacity was increased in such a manner that the maximum velocities of hydraulic cylinders went up by about 50%. With such conditions holding, experiments no. 5, 10 and 16 were conducted.

Table 1. Investigation results for the accuracy of excavator cutting tool path performance.

Exp.	Path	I_{lw} [mm]	I_{lr} [mm]	I_{ll} [mm]	I_{xy} [mm]	$I_{xy\mathrm{Max}}$ [mm]	$I_{x\mathrm{Max}}$ [mm]	$I_{y\mathrm{MAx}}$ [mm]	ΔS [%]	Notes
1	2	3	4	5	6	7	8	9	10	11
1	1	0.27	0.40	0.31	4.01	37.21	24.11	−35.85	0.08	
2	1	0.23	0.38	0.27	3.49	37.59	22.59	−36.35	0.14	no loads
3	1	0.27	0.36	0.31	3.93	41.22	21.75	−40.22	0.10	$p_z = 16\,\mathrm{MPa}$
4	1	0.38	0.60	0.53	5.52	46.50	28.36	−42.63	0.23	$p_z = 5\,\mathrm{MPa}$
5	1	0.38	0.56	0.53	5.40	45.51	27.82	−42.53	0.24	$V_{\max} = 1.5V_{\max 0}$
6	1	1.01	1.16	0.94	12.40	73.68	37.59	−69.57	0.41	change of controller settings
7	2	0.20	0.42	0.41	4.21	27.42	26.90	−18.29	0.68	
8	2	0.16	0.40	0.37	3.81	28.73	28.65	−18.27	0.62	$p_z = 16\,\mathrm{MPa}$
9	2	0.33	0.63	0.70	6.75	58.26	39.82	−48.71	1.39	$p_z = 5\,\mathrm{MPa}$
10	2	0.32	0.57	0.59	6.31	47.58	37.62	−42.11	1.21	$V_{\max} = 1.5V_{\max 0}$
11	2	0.73	1.21	1.14	12.72	74.22	58.66	−61.70	2.91	change of controller settings
12	3	0.35	0.48	0.56	4.85	33.83	−26.21	−33.52	0.39	
13	3	0.34	0.48	0.56	4.62	27.53	−25.13	−27.53	0.28	no loads
14	3	0.33	0.43	0.51	4.45	25.87	−24.94	−25.61	0.27	$p_z = 16\,\mathrm{MPa}$
15	3	0.46	0.72	1.03	7.27	53.98	51.15	−34.91	0.24	$p_z = 5\,\mathrm{MPa}$
16	3	0.41	0.67	0.95	6.52	49.83	47.43	−38.26	0.17	$V_{\max} = 1.5V_{\max 0}$
17	3	0.91	0.21	1.90	11.53	61.87	57.78	−41.30	0.45	change of controller settings
18	4	0.19	0.28	0.29	3.90	26.21	19.24	−25.94	0.24	$p_z = 16\,\mathrm{MPa}$
19	4	0.19	0.30	0.27	3.84	26.04	19.34	−25.21	0.24	$p_z = 5\,\mathrm{MPa}$
20	4	0.28	0.52	0.50	6.58	60.92	33.29	−53.31	0.63	$V_{\max} = 1.5V_{\max 0}$
21	4	0.58	0.94	0.80	11.33	76.61	−39.60	−65.71	1.80	change of controller settings

6. When breaking the aggregate, with the supply pressure $p_z = 10\,\mathrm{MPa}$ and modified digital controller settings. When carrying out experiments no. 6, 11, 17 and 21, controllers of the following settings were used:

$k_r = 4$ $T_i = 0.3$ for the outrigger,
$k_r = 6$ $T_i = 0.5$ for the arm,
$k_r = 6$ $T_i = 0.7$ for the bucket.

Lower values of amplifying factors and longer doubling periods were used when compared with the controller settings used previously, which deteriorated the control quality.

Figures 2 – 11 illustrate the experiments covered by the investigations. Figures 3 and 9 show the cutting tool paths: preset (denotation X_U and Y_U) and actual (denotation X and Y) calculated during the experiments. Moreover, for path no. 1 (Fig. 2), changes in the hydraulic cylinder lengths are shown, as well as length errors and path performance errors. Figures 4 and 5 refer to the aggregate breaking, while Figs. 6 and 7 to fittings motions without any load.

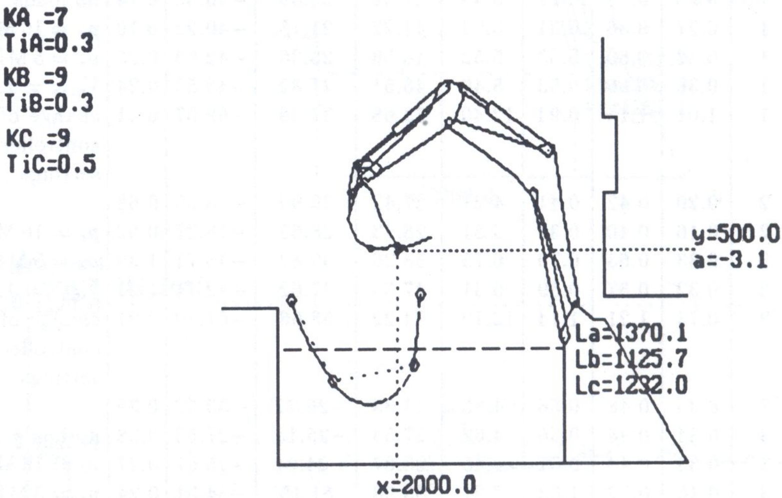

FIG. 2. Path no. 1 of the bucket cutting tool.

The error values shown in Table 1 pointed to the satisfactory accuracy of the planned paths performance. The aggregate breaking did not require large cutting forces to be applied, therefore the basic pressure of hydraulic supply of 10 MPa was employed. Under such conditions the paths were performed with an average accuracy below 5 mm. Maximum deviations of actual paths from the set ones did not exceed 40 mm. An average accuracy of the performance of set hydraulic cylinder length variations ranged from 0.2 to 0.6 mm, while the maximum dynamic deviations did not exceed 4 mm. Similar error values were obtained for fittings motions without any load.

After the supply pressure was increased to 16 MPa, no significant improvement of path performance accuracy was reported. Instead, when the supplier pressure was reduced to 5 MPa, the accuracy deteriorated as the power of the hydraulic system was too low. However, even in that case average path deviations did not exceed 7.5 mm, while the maximum deviations were 60 mm.

When the maximum velocities of hydraulic cylinders increased by 50%, average path deviations increased up to 6.5 mm, while the maximum de-

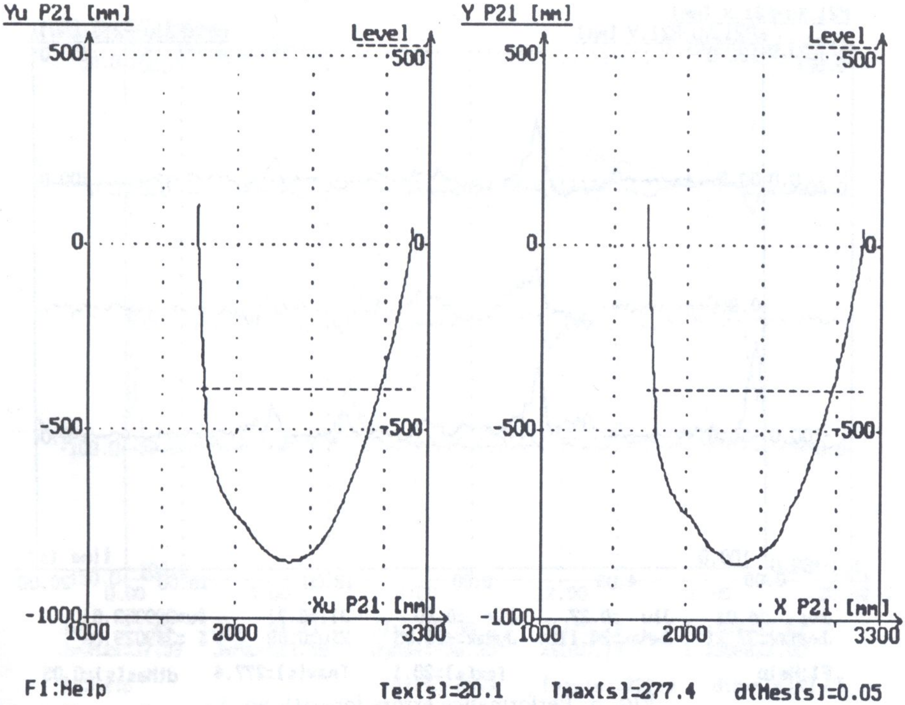

FIG. 3. Preset (notation X_U, Y_U) and actual (notation X, Y) tool paths for path no. 1.

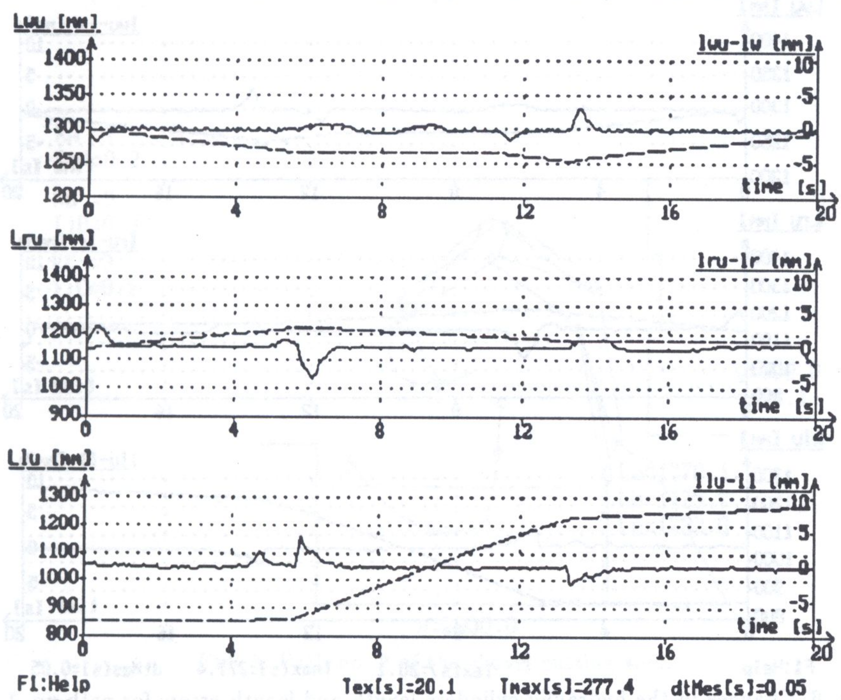

FIG. 4. Changes in the hydraulic cylinders length variations and the length errors for path no. 1.

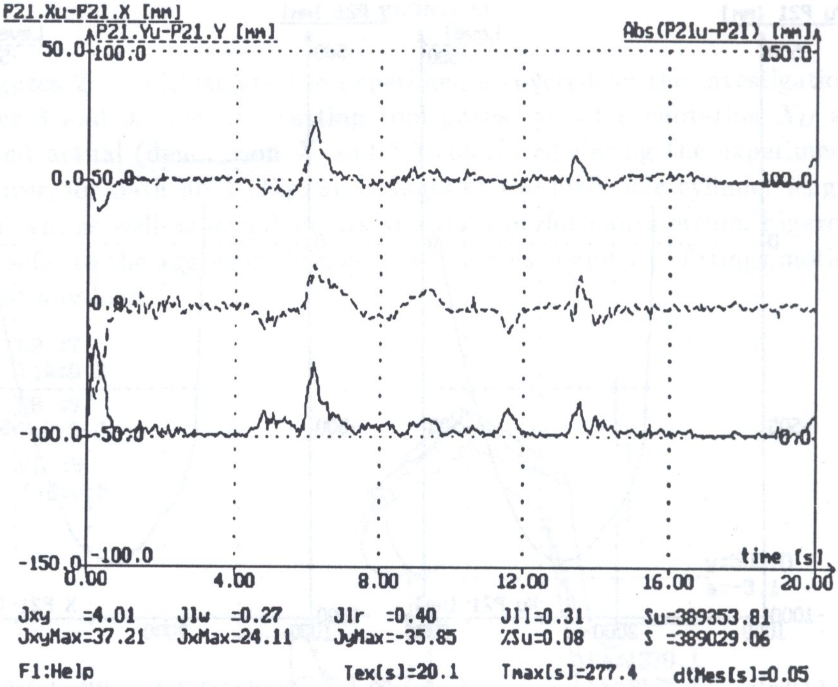

FIG. 5. Performance errors for path no. 1.

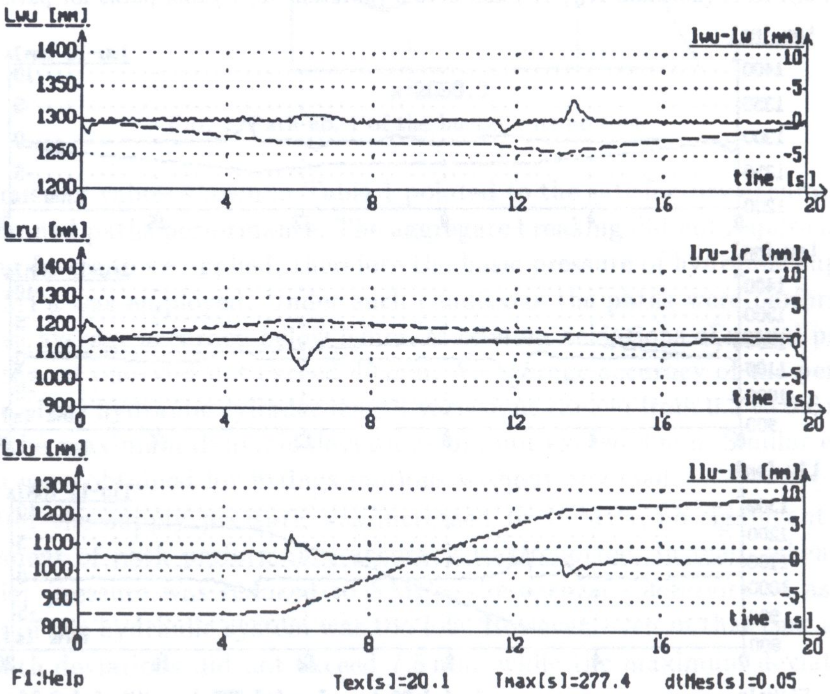

FIG. 6. Changes in the hydraulic cylinders length and length errors for path no. 1 with no load motion.

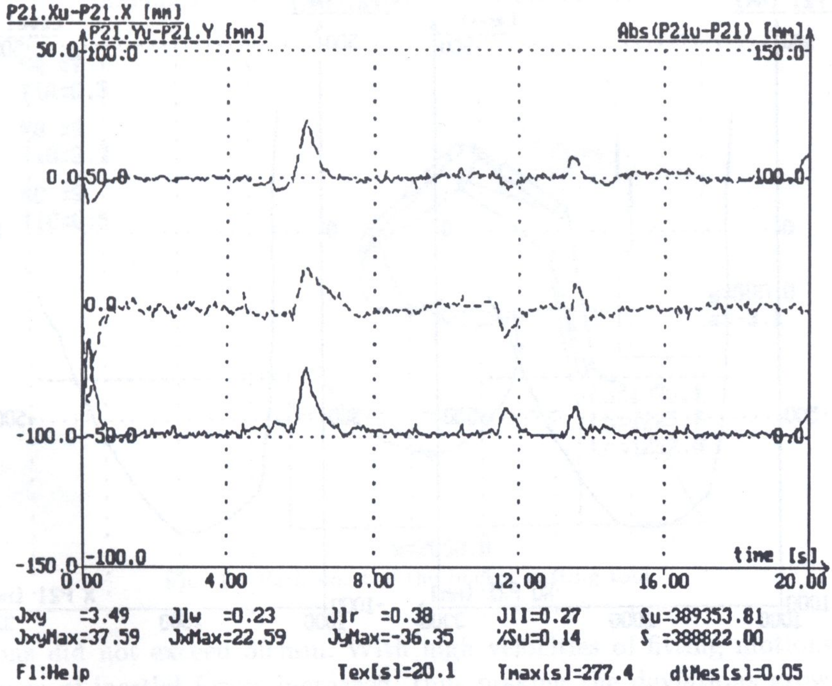

FIG. 7. Performance errors of the path no. 1 with no load motion.

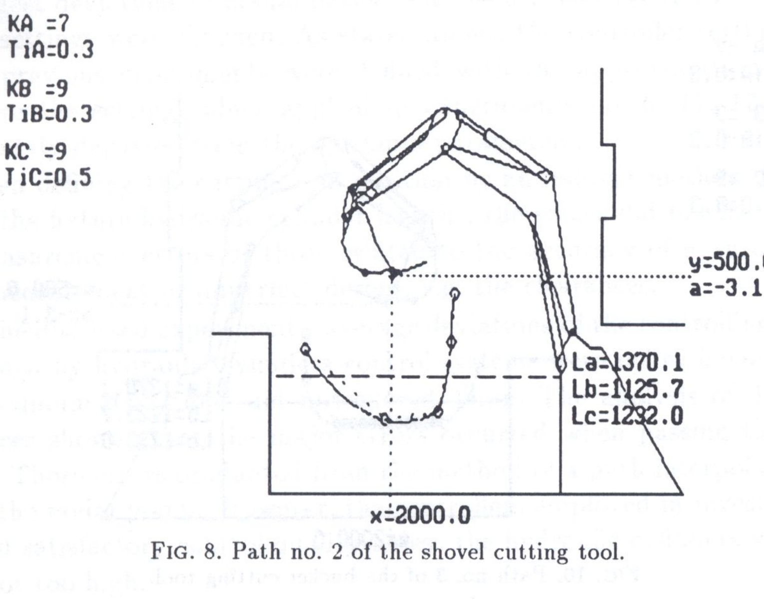

FIG. 8. Path no. 2 of the shovel cutting tool.

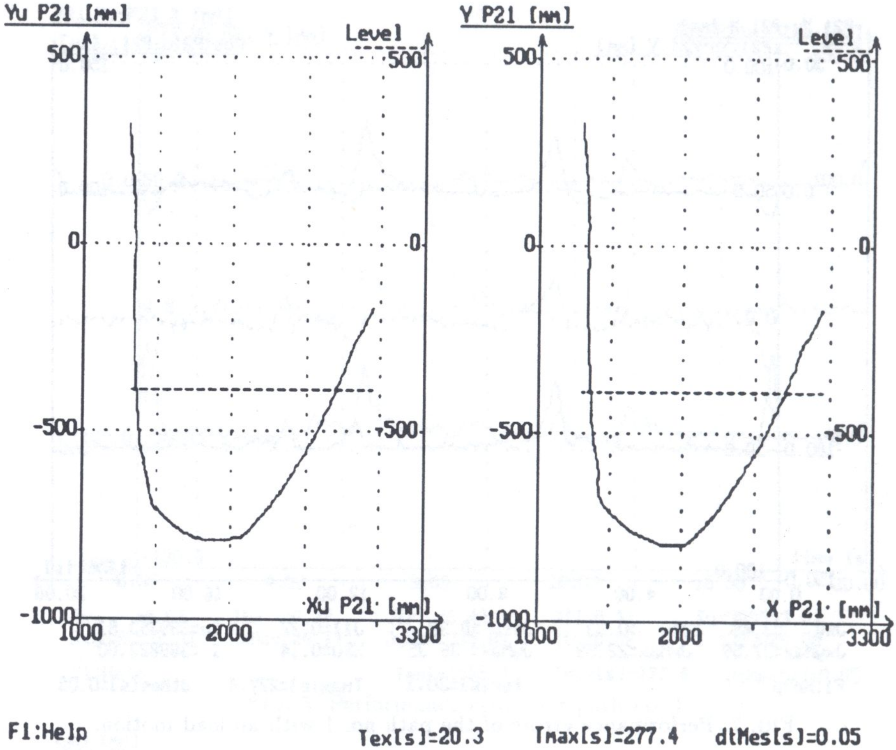

FIG. 9. Cutting tool paths: preset and actual for path no. 2.

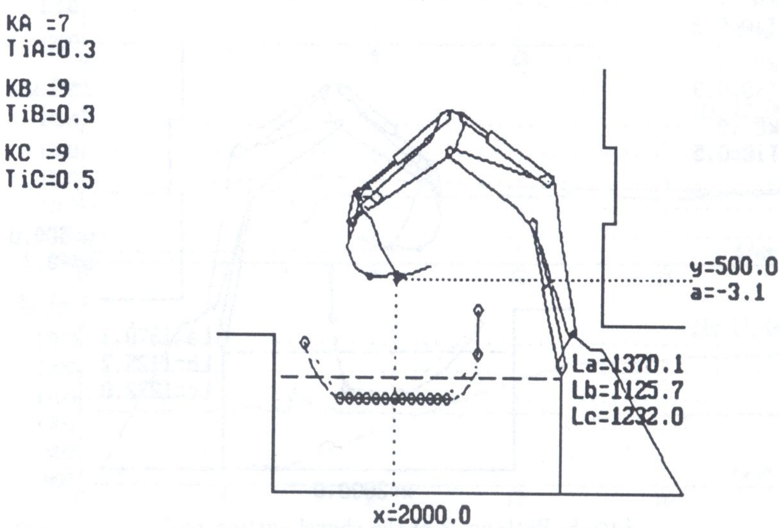

FIG. 10. Path no. 3 of the bucket cutting tool.

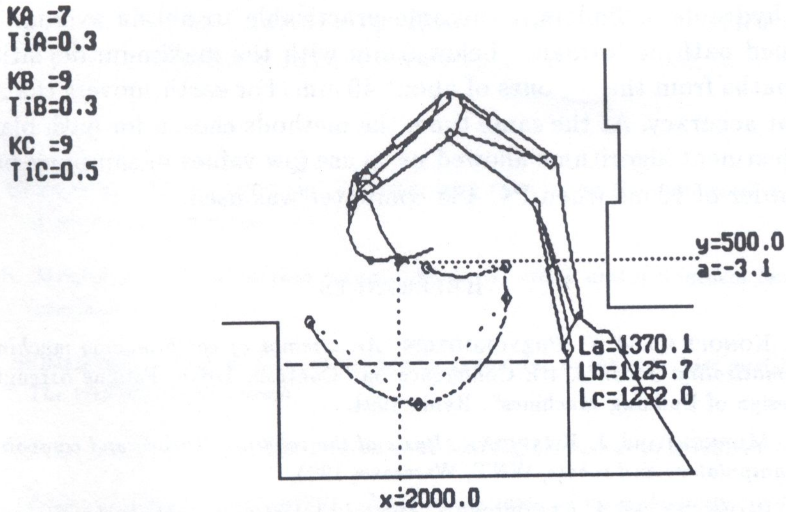

FIG. 11. Path no. 4 of the bucket cutting tool.

viations did not exceed 50 mm. With high velocities of fitting motions the influence of inertial forces increased, thus making the deviations grow due to the linear path interpolation between intermediate points, the control algorithms being employed.

In the course of experiments, the results of which were shown in Table 1, the largest deviations of actual paths from the set ones occurred when controller settings were changed. As stated above, the controller settings used in the previous experiments were defined with the approximate methods, therefore the setting values applied in experiments no. 6, 11, 17 and 21 significantly departed from the optimum parameters.

When defining the cutting tool position by an indirect method, by measuring the fixture hydraulic cylinder lengths, the values did not incorporate the measurement errors or those related to the accuracy of fixture dimensions measurement or imperfect design, e.g. the clearances.

In the discussed experiments, average deviations of the controlling signals performed by hydraulic cylinders control systems were below 0.6 mm while the maximum deviations did not exceed 4 mm. The analysis of deviation sequences showed that the major errors occurred when passing the nodal points. Those errors originated from the method of a path interpolation between the nodal points. However, the controllers employed in investigations ensured satisfactory control quality unless the hydraulic cylinders velocities were not too high.

The experiments proved that in simple methods of interpolation of shovel cutting tool path and fairly simple algorithms of position adjustment of fixture hydraulic cylinders, it became practicable to obtain average errors of planned path performance below 5 mm with the maximum deviations of actual paths from the set ones of about 40 mm. For earth-movers that was a sufficient accuracy. At the same time, the methods chosen for path planning and adjustment algorithms allowed us to use low values of sampling periods of the order of 10 ms when PC 486 computer was used.

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