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DIGITAL CONTROLLED HYDRAULIC DRIVES OF WORKING MACHINES

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The paper is aimed at discussing the monitored control systems with different regulation algorithms, exemplified by a linear hydraulic drive. Results of experiments concerning the drives of a single bucket hydraulic digger are presented in order to compare the regulation quality in the cases discussed.

1. INTRODUCTION

Hydraulic drives have been widely used in metal-working machines, presses, laboratory strength testing and simulation machines and in other working machines. In recent years the progress in hydraulic drives was associated with the introduction of new, improved elements, mainly the distribution valves of continuous action and variable delivery pumps, as well as with application of electronics, in particular the digital technology.

Many novel solutions of hydraulic drive and control are being introduced in working machines. This is a result of a high number of such machines and of their prices, what allows the leading manufacturers to invest considerable funds in development works.

The supply system of earth moving machines has been recently modernized by introducting variable delivery pumps controlled by digital systems, what improves the energy economy (savings up to 30%) and increases their capabilities by raising the supply pressure up to 32 MPa.

Modern earth moving machines are also equipped with the monitoring system which enables the operator to control the positions of machine tools and to determine the disposable force. Attempts are also made to introduce the systems capable of automatizing the operation of the machine accessories, what is associated with application of a monitored system controlling the position and velocity of the hydraulic cylinder piston. This is possible owing to the introduction of proportional control valves, such as those produced by BOSCH and MANNESNANN REXROTH. The valves have much better dynamic characteristics than the proportional valves used at present in the equipment of working machines, and their requirements concerning oil filtration are lower than those of straight run servovalves. Consequently, it is possible to use the regulation type proportional valves in earth moving machines, whereas servovalves are mainly applied in laboratories or in aviation.

The DIGDIGG (for Digital Digger) digital control system of hydraulic digger equipment and the station for testing the control systems of equipment of the K–111 digger made by Z.M. "Waryński" have been built in the Kielce Branch of the Institute of Fundamental Technological Research within the framework of research project on the digital control of hydraulic drives [2, 3, 4].

In order to automatize the motions of the equipment, the system prepares the necessary commands for systems controlling the positions of hydraulic cylinders of the outrigger, its arm and the bucket. The method of preparing the commands depends on the used programming procedure of equipment motions.

It is possible to program by means of the multipoint "teach-in" method, to apply the computer-calculated continuous control (CPC), or use the "point to point" (PTP) method [4]. Quality of realization of the programmed trajectory by all these methods depends mainly on the control quality of position of the cylinders.

The control systems tested were digital systems based on a IBM PC/AT microcomputer with a 10 MHz clock and 80286 processor provided with analog-to-digital and digital-to-analog converters. Hydraulic cylinders of the digger were operated by MANNESMANN REXROTH 40WRE 10 proportional control valves. Feedback signals for control systems came from PELTROM PJ×500 inductive sensors fitted on the hydraulic cylinders.

In what follows, the methods of digital control of linear hydraulic drives are discussed and results of experimental tests on cylinder position control systems of the hydraulic equipment are presented.

2. MODEL OF CONTROLLED PLANT AND ITS IDENTIFICATION

The required control quality in the DIGDIGG system is obtained by parametric optimization of the controllers.

Mathematical model of the controlled plant is used for selection of controller settings, because it was found that the experiments performed on the actual system do not ensure such repeatability of results as that required for optimization. Besides, the plant model is necessary for constructing the state observer, which is described below.

For the plant in the form of valve-operated linear drive, the object model can be assumed in the form of elements connected in series, representing the control valve and the hydraulic cylinder with load. Similar model can be assumed for the rotational drive, and hence, conclusions drawn from the analysis of a hydraulic cylinder drive can be transferred to the valve-operated rotational drive, as shown in Fig. 1.

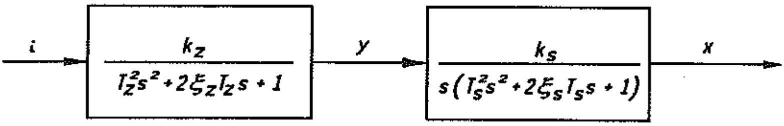

FIG. 1. Linearized model of controlled plant.

The transfer function of the valve can be assumed in the form [1, 4]

$$G_z(s) = \frac{y(s)}{i(s)} = \frac{k_z}{T_z^2 s^2 + 2\xi_z T_z s + 1}, \tag{2.1}$$

where y – displacement of distributor slide, i – control current. The transfer function (operational transmittance) of the hydraulic cylinder takes the form

$$G_s(s) = \frac{x(s)}{y(s)} = \frac{k_s}{s(T_s^2 s^2 + 2\xi_s T_s s + 1}, \tag{2.2}$$

where x – displacement of cylinder piston.

The plant is thus the fifth-order system, and for its identification four parameters, i.e. T_z, ξ_z, T_s, and ξ_s $k = k_z k_s$ should be determined. Application of the fifth-order model for the state observer considerably prolongs the numerical computation time and, therefore, the simplified, linearized plant model has been assumed for further research as the third-order system with the following transfer function

$$G(s) = \frac{x(s)}{i(s)} = \frac{k_m}{s} \, \frac{1}{T_m^2 s^2 + 2\xi T_m s + 1} \tag{2.3}$$

representing a series connection of the integrating and oscillatory elements.

The transfer function (2.3) is an approximation of a typical transfer function of the astatic plant,

$$G(s) = e^{-\tau s}\frac{1}{Ts}\,. \tag{2.4}$$

In the DIGDIGG system the gradient-free Hooke - Jeeves method [3] is used for of determination of the straight lines necessary for identification of the controlled plant, as well as for parametric optimization of the controllers. For identification of the plant we have recorded the variation of cylinder displacements representing the response to a sequence of jump-like disturbances; then we have optimized parameters of the plant using the objective function in the form

$$I_2 = \sum_{i=1}^{n}\left[x(t_i) - x^*(t_i)\right]^2 , \tag{2.5}$$

where $x(t)$ – output signal of the model, $x^*(t)$ – response signal of the actual plant.

Several results of model identification for the digger arm drive are shown in Fig. 2, and in Table 1 identification results for all the controlled plants are given.

Optimum selection of model parameters

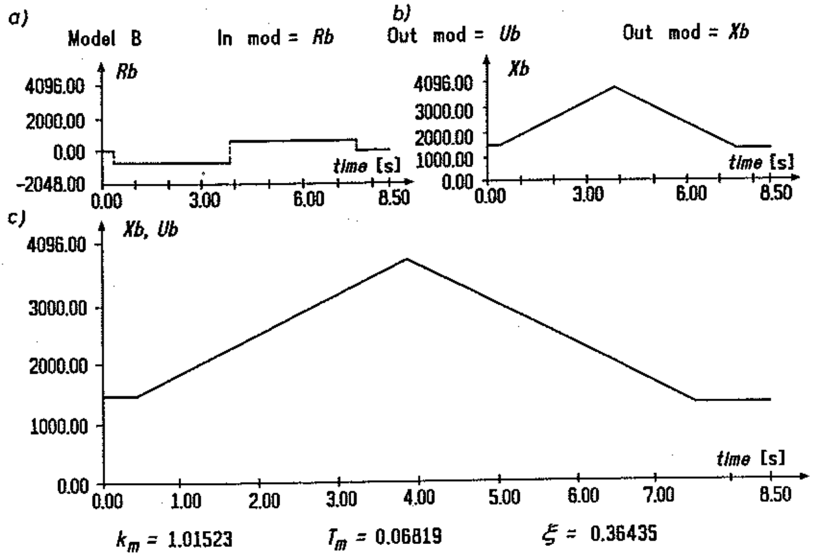

FIG. 2. Identification of digger arm drive, a) input signal; b) object response; c) object and response of the identified model.

Table 1. Identification results

	Outrigger	Arm	Bucket
K	0.5797827	1.01522314	1.2245028
T	0.0696177	0.0681936	0.058033
ξ	0.3620703	0.3643469	0.5182507

3. PID CONTROL

The digital PID controllers used realize the algorithms being numerical versions of algorithms of the conventional continuous-time PID controllers. In the case of the hydraulic cylinder position control system, the feedback comes from the displacement signal only (Fig. 3). Continuous-time algorithms of the PID control are approximated in numerical systems by positional or incremental algorithms. In view of discrete integration and differentiation of the error signal, the algorithms are particular versions of the continuous-time algorithm of the PID control of the form

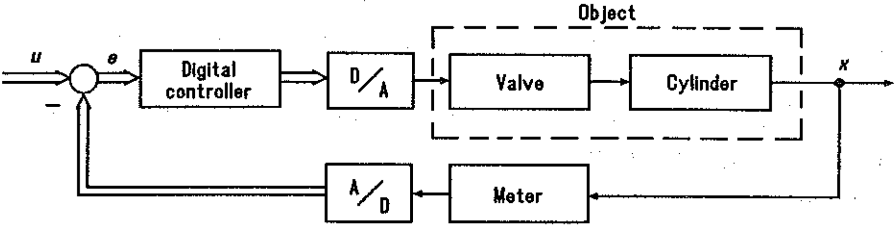

FIG. 3. Diagram of position control system with displacement signal feedback.

$$R(t) = k_r \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau + T_d \frac{de(t)}{dt} \right]. \tag{3.1}$$

The discrete-time positional PID algorithm takes the form

$$R_0 = k_r e_0 + T_i' \sum_{n=0}^{j} e_n + T_d'(e_0 - e_1), \tag{3.2}$$

where

$$k_r = k_p, \qquad T_i' = \frac{k_p T_p}{T_i}, \qquad T_d' = \frac{k_p T_d}{T_p},$$

$$e_1 = e(t - T_p), \qquad e_0 = e(t) \quad - \quad \text{error},$$

k_p, T_i, T_d – controller settings, T_p – sampling period;

summation is performed for successive sampling instants. The incremental PID algorithm takes the form

$$R_0 = R_1 + \Delta R = R_1 + k_r(e_0 - e_1) + T_i' e_0 + T_d'(e_2 + e_0 - 2e_1), \tag{3.3}$$

where

$$R_0 = R(t), \qquad R_1 = R(t - T_p), \qquad e_2 = e(t - 2T_p).$$

In order to compensate the nonlinearity of the object in linear drives, additional periodical signal with suitably selected frequency and amplitude, the so-called "dither", is applied to the controller. It especially applies to systems with hysteresis, where the dither reduces the possibility of stagnation by unbalancing the system from the zone of insensitivity.

Application of the dither to a digital controller consists in introduction of a rectangular signal with the half-period corresponding to the sampling period of its multiple.

PID controllers acting according to the positional algorithm (3.2) have been used in the DIGDIGG system.

Controller settings have been determined by optimization based on the plant models with parameters shown in Table 1. For the optimization, the Hooke-Jeeves procedure is used, like in the case of identification of the controlled plants. Figures 5 and 6 show the results of experimental tests

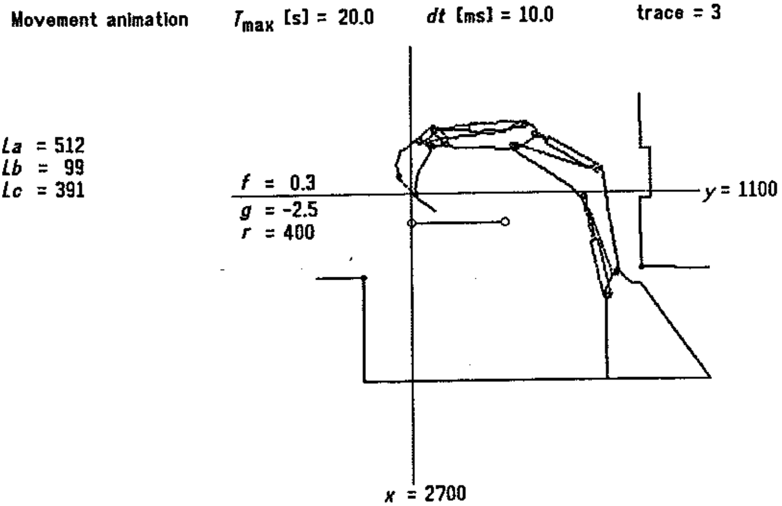

FIG. 4. Set trajectory of digger bucket edge.

of a digger with the PID control. Figure 5 shows the trajectories of control signals for the outrigger (a), arm (b) and bucket (c), programmed by the PTP procedure for the movement of the bucket cutting edge along the path $A \to B \to A$, as shown in Fig. 4. This case will be used further in this paper to show operation of the digger equipment control performed by other control methods enabling us to compare the control quality. Successive Figs. 6 abc show the signal trajectories during the programmed digger equipment motions.

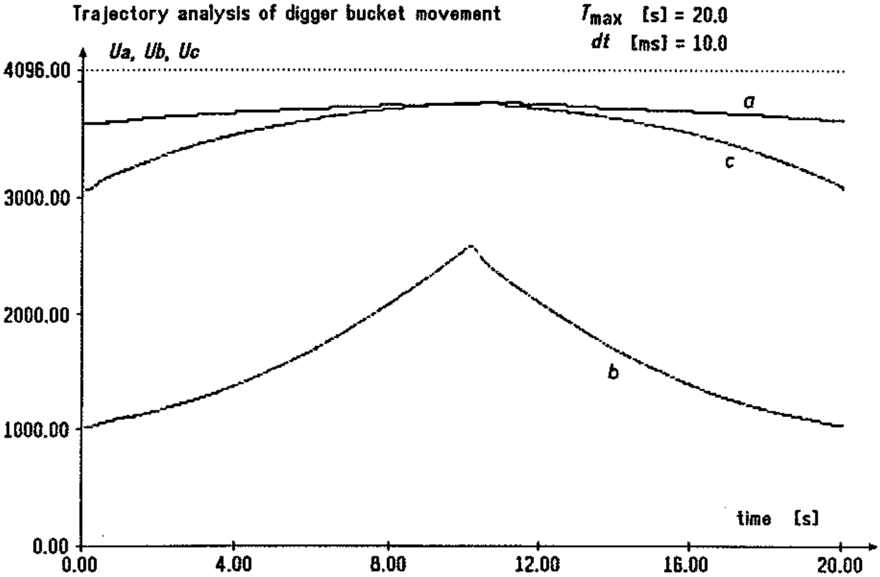

FIG. 5. Trajectories of commands for movement along horizontal segment (acc. to Fig. 4).

The command and cylinder displacement signals are superimposed, and the trajectory of the controller output signal is drawn below. The optimum settings of PID controllers are also shown in the figures. Experiments have been perfermed with the sampling period of 10 ms. The control quality is determined by the mean square value of the index of quality as follows

$$I_2 = \sum_{i=1}^{n} [u(t_i) - x(t_i)]^2 . \tag{3.4}$$

For 2000 measuring points used in the discussed case, the values of the index for the outrigger, arm and bucket were equal, respectively, to

$$I_{2A} = 28950, \qquad I_{2B} = 93150, \qquad I_{2C} = 23500.$$

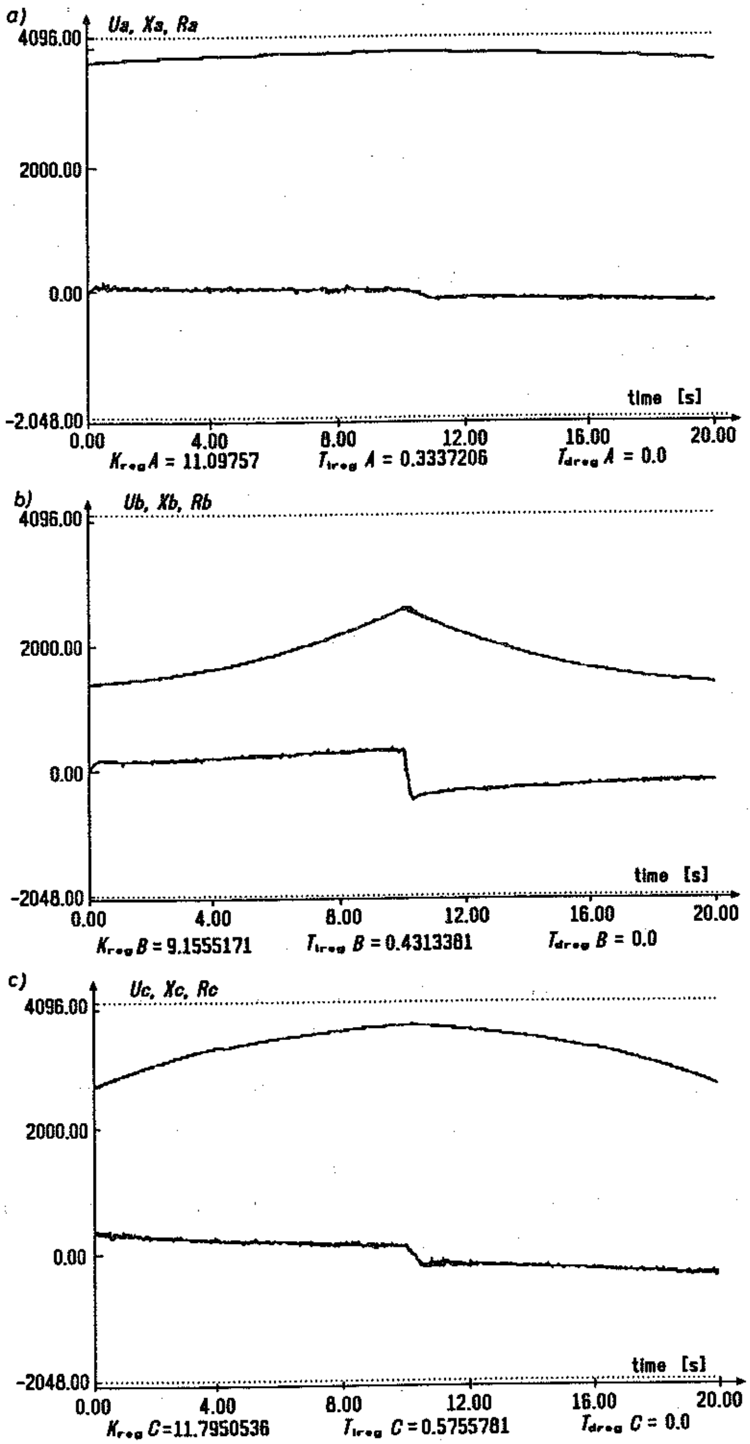

FIG. 6. Signals for digger bucket movement along horizontal segment, a) outrigger; b) arm; c) bucket. PID controllers with parameters as shown under Figures.

Values of the index, as well as values of the signals in all figures are in units of the analog-to-digital converter. Trajectories of signals in Fig. 6 confirm good quality of the PID control.

4. STATE CONTROLLER

In order to generate the control signal in conventional PID controller the displacement error is only used. The state controller enables us to take into account such quantities as velocity and acceleration in the control process.

The regulation algorithm for the state controller has the form

$$R_i = k_r\,[u(t_i) - x(t_i)] - k_d\,\overset{\prime}{x}\,(t_i) - k_{dd}\,\overset{\prime\prime}{x}\,(t_i). \tag{4.1}$$

The block diagram of the control system with the state controller is shown in Fig. 7. Utilization of velocity and acceleration feedbacks enables us to apply greater values of controller amplification coefficient k_r than that used in the conventional PID controller. State controllers are recommended when the natural frequency of the control valve is at least two times greater than the natural frequency of the hydraulic cylinder [1]. The recently manufactured proportional valves and servovalves have much greater natural frequencies and, therefore, they play a more important role in the design of the position control systems for linear drives.

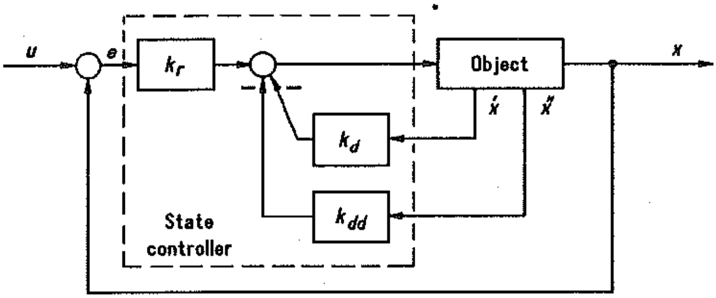

FIG. 7. Diagram of position control system with state controller.

Position of the cylinder piston is the only measurement taken in most cases of linear drives. Simultaneous measurements of the position, velocity and acceleration are not applied in working machines. Therefore, the signals necessary for operation of the state controller (4.1) must be obtained by differentiation of the displacement signal or by other methods. Application of the acceleration sensor and subsequent integration of its signal is not used in practice in view of the measurement problems involved and because it is difficult to record the signal in the steady state (at rest).

Numerical differentiation of signals causes many problems connected with noise, because their differentiation considerably distorts the resulting signal. Filtration of averaging of the results obtained is used in order to minimize the noise effects.

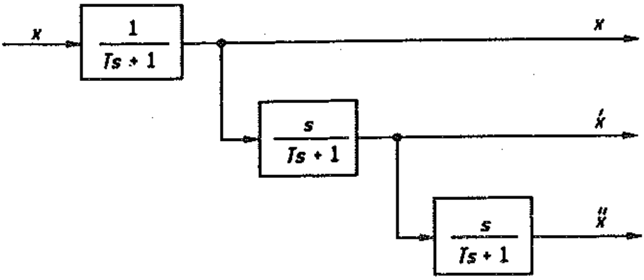

FIG. 8. Diagram of signal filtration and differentiation.

Filtration of signals illustrated by Fig. 8 is used in the DIGDIGG system. Filter time constants amounted to $T_f = 5T_p$, where T_p was the sampling period. Figure 9 shows the example of differentiation of the harmonic signal composed of a sine wave $u(t) = 1200\sin(0.4\pi)$ and of a superimposed noise of normal distribution within the range of ±5. It was found that the presented method of differentiation may be used for construction of the state controller.

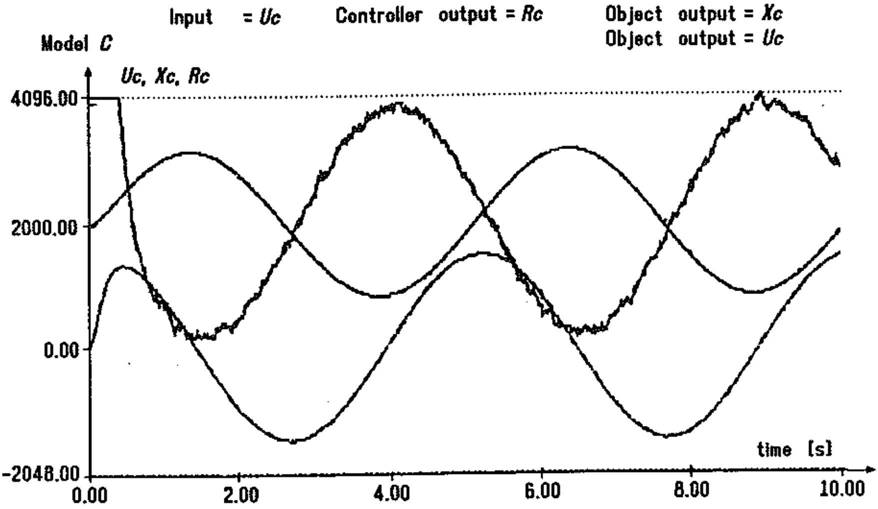

FIG. 9. Example of harmonic signal differentiation.

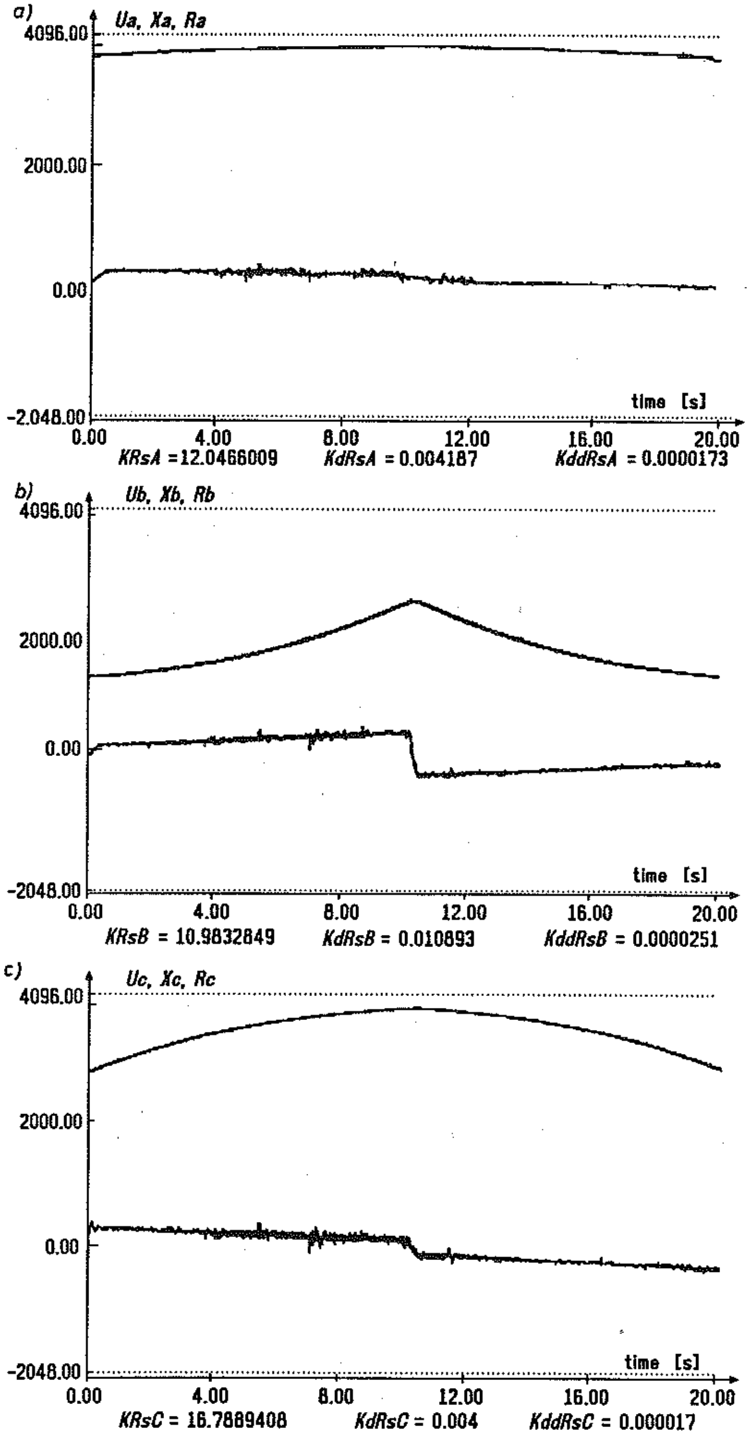

FIG. 10. Diagrams of signals for digger bucket movement along a horizontal segment with application of state controllers, a) outrigger; b) arm; c) bucket.

Optimum values of state controller coefficients (4.1) can be determined by the optimization methods similar to those applied in the PID controllers. Figure 10 shows the trajectories of signals corresponding to the horizontal motion of the bucket of an actual digger, determined on the testing stand, as well as optimum parameters of the controllers. Values of the I_2 index (3.3) for the system with state controllers and for the motion shown in Fig. 10 were equal to

$$I_{2A} = 33200, \qquad I_{2B} = 139483, \qquad I_{2C} = 41392.$$

The index values indicate the control quality to be inferior to that of PID controllers. It is connected with the nature of commands. In working machines, where the basic working motions are performed at a low velocity along circular arcs and straight line segments, the commands are too smooth to show advantages of the state controllers. The state controllers enable us to follow quick changes of the commands and, in such a case, the control results are better than those of the PID control. Lack of integral action also leads to inferior control results. Indeed, in state controllers we can apply greater values of the amplification coefficient than those in the PID controllers, but for commands increasing in a linear manner, astaticism of the first order system resulting from the plant character, does not enable us to eliminate the static error, what can be seen in Fig. 10.

5. CONTROLLER WITH STATE OBSERVER

Application of the state controllers described above does not bring the expected results, also on account of the applied method of determination of velocity and the acceleration signals. It can be supposed that a certain improvement of the control quality by means of the state controller could be obtained if all signals required for its operation were derived from measurements.

In order to avoid the difficulties connected with differentiation of the displacement signal in the system with state controller, one can apply the so-called "state observer", which represents a kind of controlled plant model. The input signal acting on this model is the same as that acting on the real plant. As a result of the model operation we obtain estimates of the velocity and acceleration signals which can be utilized by the state controller. The displacement signal comes from the measurements taken at the real plant.

In this approach the coincidence of signals obtained from the state observer with real signals depends on the quality of the object identification. In order to improve the coincidence of signals, the correction feedback is applied in the observer as shown in Fig. 11.

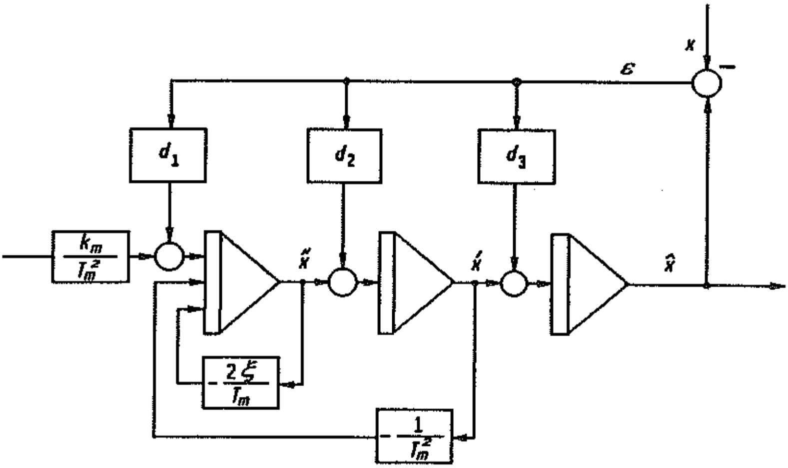

FIG. 11. State observer with equalizers.

The displacement signals: x of the real plant and $\hat{x}$ of the model are compared with each other in the output of the state observer. The difference (suitably amplified) is used in the model correction to reduce $\hat{x} - x$ to zero.

Figure 12 illustrates the operation of equalizers. Model of the outrigger drive with parameters given in Table 1 is used here as the plant model. Value of the model amplification factor in the state observer was reduced from 0.58 to 0.48. Application of equalizers for the $d_{1,2,3}$ factors (given in Fig. 12a) makes the displacement, velocity and acceleration signals coincide under harmonic input conditions. Values of $d_{1,2,3}$ were obtained by optimization. Consequently, signals from the state observer can be used to produce the state controller signal accounted to Eq. (3.4). The velocity and acceleration signals in the DIGDIGG system with state controller are worked out using state observers as shown in Fig. 11.

Figure 13 shows trajectories of signals for the motions shown in Fig. 4, determined on the testing stand for the actual digger. Controller parameters are given in Fig. 10. Quality of control is somewhat better than that achieved by the state controller with differentiation of the displacement signal, but worse than that in case of the PID controller. Explanation is similar to the remarks given in Sec. 4.

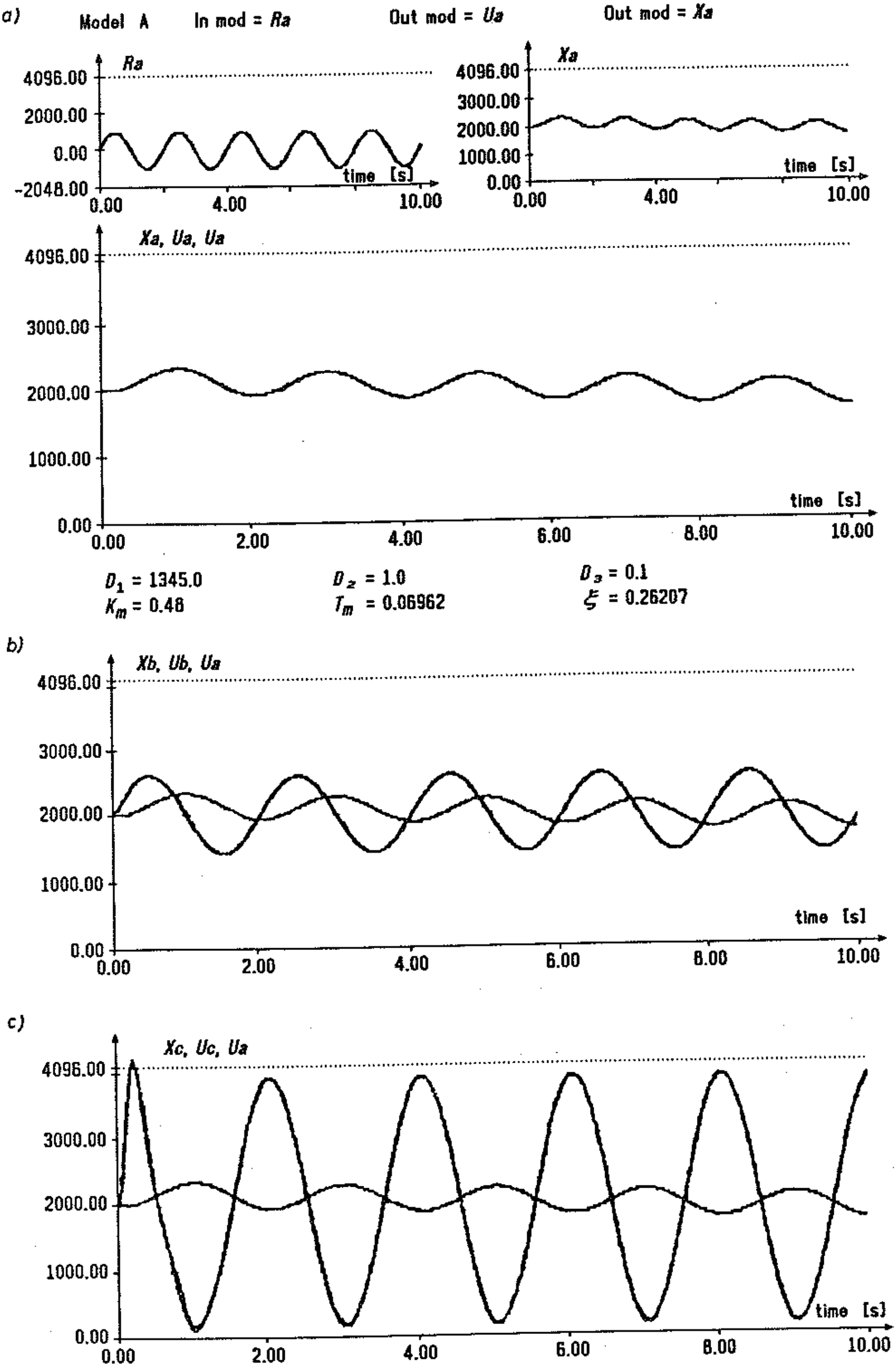

FIG. 12. Operation of state observer equalizers, a) displacement; b) velocity; c) acceleration.

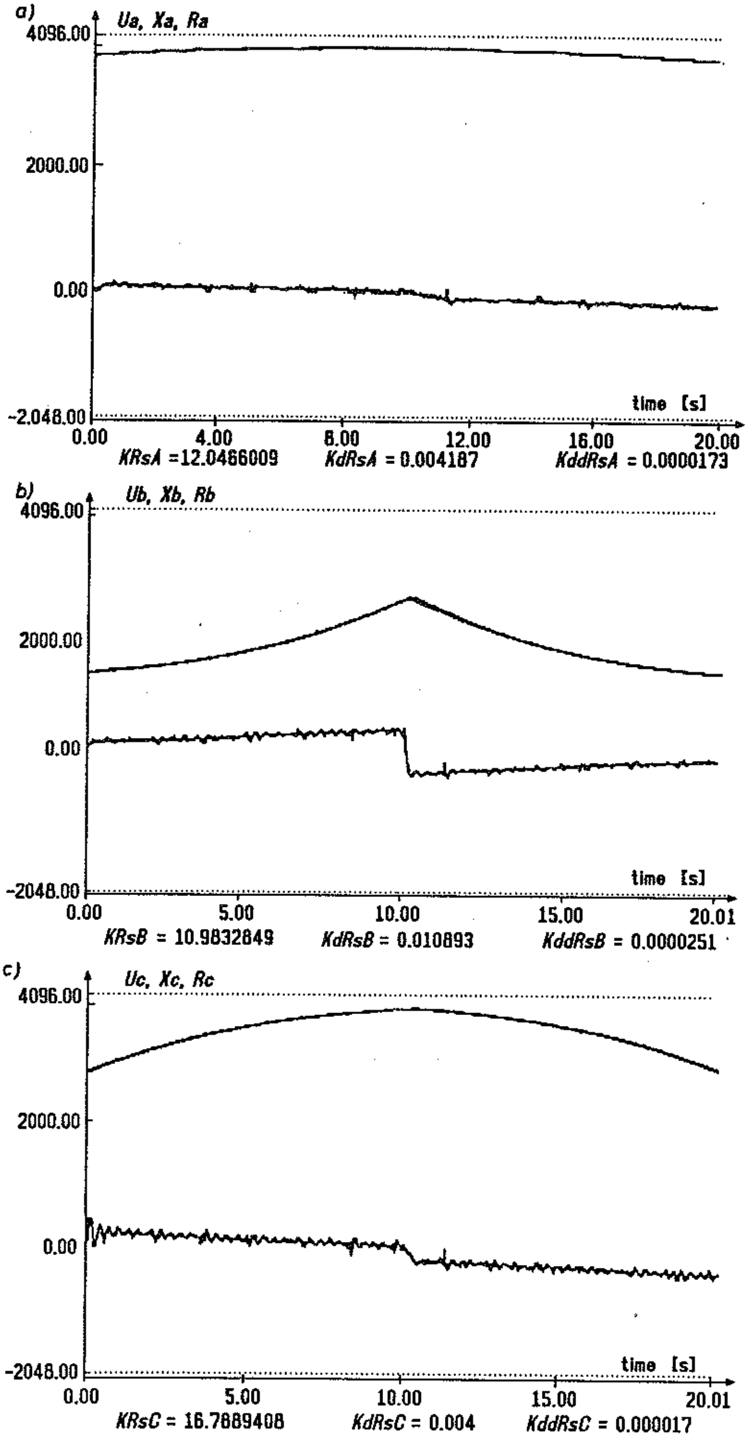

FIG. 13. Diagrams of signals for digger bucket movement along horizontal segment with application of controllers with state observers, a) outrigger; b) arm; c) bucket.

6. State controller with integration

Introduction of integral action to the control system with the 1-st order astatic plant is necessary to eliminate the static errors due to a linear noise growth. Hence, state controllers with additional error integration was also proposed for the DIGDIGG system. Algorithm of digital control takes the form

$$R_i = k_r e(t_i) - k_d \overset{\prime}{x}(t_i) - k_{dd} \overset{\prime\prime}{x}(t_i) + T_i \sum_{n=0}^{i} e_n . \tag{6.1}$$

The $\overset{\prime}{x}(t)$ and $\overset{\prime\prime}{x}(t)$ signals can be obtained by differentiation of the $x(t)$ signal or by the state observer.

The tests results presented in Secs. 3 and 4 indicate that application of the state observer is more advantageous, and this method of determination of the $\overset{\prime}{x}(t)$ and $\overset{\prime\prime}{x}(t)$ signals has been used for the digger control in the DIGDIGG system. The control algorithm (6.1) is equivalent to the PIDD [2] control algorithm in which only the controlled variable is differentiated, not the error. This type of algorithm is used in order to avoid differentiation of the prescribed value, what is important in view of its abrupt changes.

Simulation tests and experiments performed in the test station with the digger equipment confirms good control quality at the discussed control algorithm. In the case of horizontal motion of the digger bucket shown in Fig. 4, the following values of the control index have been obtained for optimal control parameters and for the velocity and acceleration signals determined by differentiation

$$I_{2A} = 23000, \qquad I_{2B} = 77050, \qquad I_{2C} = 21020.$$

The results obtained show that the control quality of state controllers with integration is much better than the control quality of PID control and state controllers whithout integration. Figure 14 shows some trajectories of signals and parameters of state controllers with integration for control of the actual digger with the desired trajectory as shown in Fig. 4. Velocity and acceleration signals were in this case obtained by means of the state observers, what made it necessary to increase the sampling period up to 15 ms. Trajectories of the signals indicate good control quality, what is confirmed by observation of the bucket edge trajectory described in [4].

The best control quality for the state controllers with integration was also obtained in cases of other trajectories of the bucket edge, e.g. the motions along circular arcs triangles vertical and oblique straight line segments.

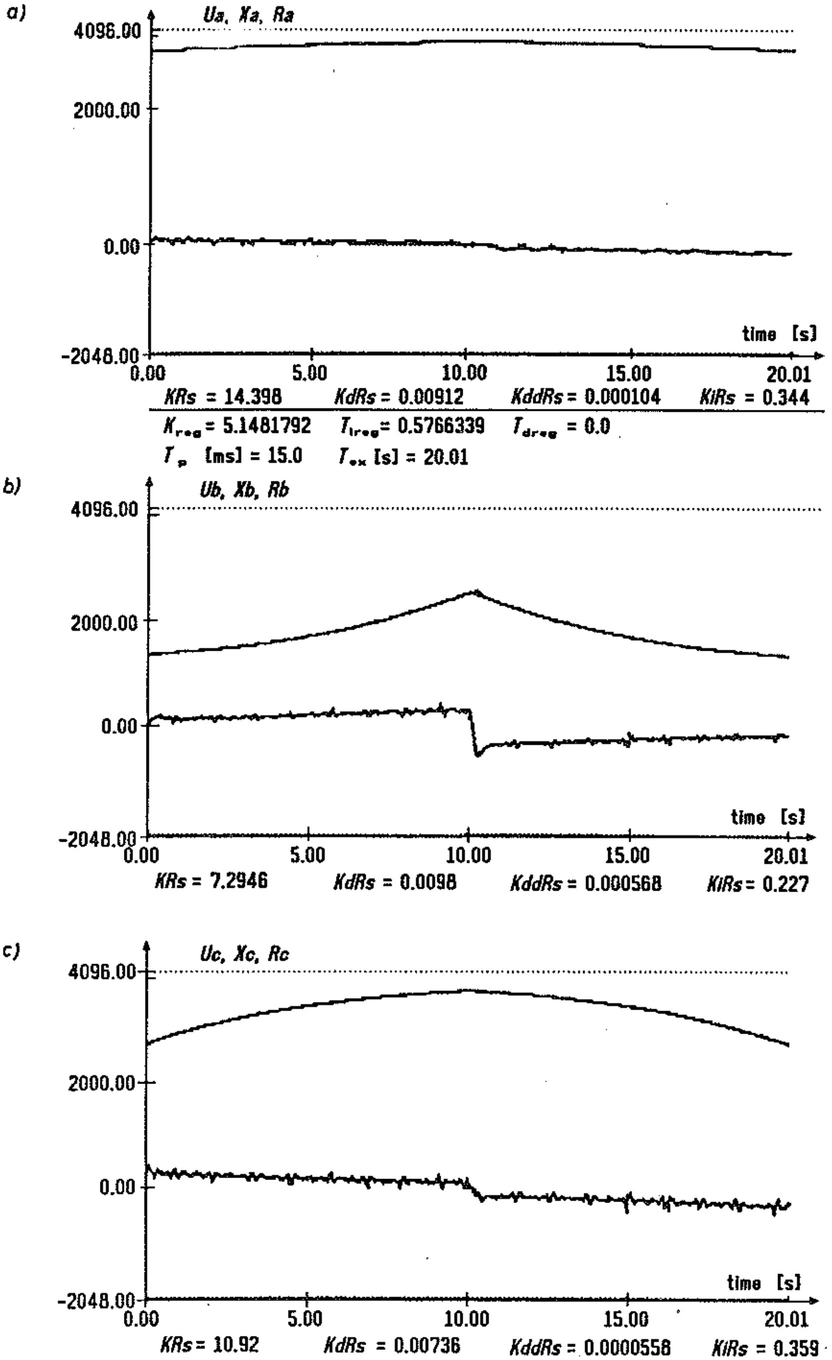

FIG. 14. Diagrams of signals for bucket movement along horizontal segment with application of state controllers with integration, a) outrigger; b) arm; c) bucket.

7. Conclusions

The simulation and experimental tests performed enable us to draw certain conclusions concerning the digital control of working machine drives, i.e. the digger drives.

1. In digital control systems of cylinder positions the best results are obtained by applying the controllers with integral action, i.e. the PID controllers and the state controllers with integration.

2. Realization of the algorithms for the state controllers with integration is more complicated than for the PID controllers since it necessitates the construction of the state observer. In the case of typical applications of hydraulic diggers, the digital version of PID controllers can be used in digital control systems of the equipment.

3. In the case of indirect control of motions of the digger bucket, i.e. by means of the equipment cylinder position control, even a very good quality of the cylinder position control does not ensure a comparably good quality of reproduction of the programmed motions. Further improvement of the reproduction quality of the motions can be obtained by modification of the commands as well as by proper adaptation of the structure and manufacturing precision of the digger equipment to the requirements of modern robotic machines.

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