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CONCEPT OF A FLEXIBLE MICROPROCESSOR SYSTEM OF CONTROLLING ELECTRO-HYDRAULIC DRIVES OF BUILDING MACHINES

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Abstract

This paper presents a concept of a microprocessor control system with flexible structure and parameters, designed for steering and positioning working components of machines driven by electro-hydraulic systems. An idea for decomposition of a block structure of the control system was presented, as well as the idea of transposing block structure into a machine readable form. Also, an example of the concept of a single-circuit control system for one of the segments of a concrete pump extension arm has been given. Results of simulation tests and experimental data for a concrete pump and hydraulic excavator made in Poland are also provided.

1. Introduction

Technological progress in the development of reliable, ever more powerful and relatively inexpensive microprocessor systems has opened completely new construction perspectives also in those fields of engineering, which could be regarded as traditionally conservative, e.g. in building machines.

Remotely controlled building machines designed for operation under hazardous for direct operators conditions, efficient use of energy or automation and monitoring of machine performance cannot be resolved by applying mechanical, electromechanical or relay systems. Symbiosis of hydraulics and electronics has become a fact and the effect in the future cannot be over-emphasized.

Electro-hydraulic systems use in building machines are exceptionally complicated non-linear [1] dynamic systems with distributed parameters. So, an attempt to linearize the dynamic model of a concrete pump extension arm [1] leads after reduction to an 8-th order system in vicinity of the operating point. Non-stationary status of the object caused by rheology, change of model descriptions caused by changes in order, strong non-linearity effects, such as stick-slip, make automation of objects of this type particularly complicated. The unprecedented recent development of linguistic logic applications for building of low sensitivity high output controllers without creating an analytical description of the controlled object gives hope for more rapid progress in automation of complicated objects such as these.

On the automation side, each building machine may be considered as a multidimensional automation system. Linearization and decoupling enables decomposition of such a complicated object into systems of low sensitivity or non-sensitive to cross-coupling, i.e. into systems having a certain degree of autonomy. This paper presents a concept of a reliable, convenient in application control system with programmed structure and parameters, made in particular for automation of local constructional units and, especially, of working units of building machines.

The following classification of control systems using microprocessor technique shall be used in this paper:

- rigid systems with unalterable structure and parameters;
- parametrized systems with rigid structure and variable parameters
- flexible systems with freely selectable structure and parameters.

It seems that most attention should be given to the group of microprocessor systems allowing free, though understandably restricted, selection of both structure as well as controlled parameters. This is particularly important when implementing adaptive, self-tuning algorithms, when parameters of the controlled object are being changed, etc.

A concept of such a system will be presented below, assuming additionally, that shaping of control system properties should be performed using only software tools, without any hardware modifications. This concept of a control system allows for setting its structure and parameters through local or remote interaction with an operator console, external higher level control system or directly by the operator.

Such concept is justified because of the following practical reasons:

- the operator receives a tool permitting him to reproduce in a software environment a parameter control system presented as a block scheme of the type commonly used in automation;
- the operator or an external hierarchically higher control system can alter the structure itself or just parameter values of the control systems according to given requirements with consideration of natural limitations using software tools, only.

To implement this concept, it was necessary to find a method of decomposing the structure of block control systems and to transpose such a decomposed block type structure into machine readable form.

2. Decomposition of a control system block structure

A linear automation system with m inputs and n outputs mat be described by a transmittance matrix G(s):

$$G(s) = \begin{bmatrix} G_{11}(s)\, G_{12}(s)\, G_{1m}(s) \\ G_{21}(s)\, G_{22}(s)\, G_{2m}(s) \\ \\ G_{n1}(s)\, G_{n2}(s)\, G_{nm}(s) \end{bmatrix} \tag{1}$$

where: $G_{ik}(s)$ transmittances are equal to the ratio of Laplace transforms of the i-th output value to transform of the k-th input value assuming that all other inputs and outputs as well as boundary conditions are equal zero.

The G(s) matrix may be transformed into the following column hypermatrix:

$$G(s) = \begin{bmatrix} G_1^{((1,,m)}(s) \\ G_2^{(1,m)}(s) \\ \\ G_n^{(1,m)}(s) \end{bmatrix} \tag{2}$$

where: $G_i^{(l,m)}(s) = [\, G_{i1}(s)\; G_{i2}(s) \;....\; G_{im}(s)]$.

Hence, each linear system with m inputs and n outputs may be decompose in to n disjoint components with one output and m inputs.

Such a scheme will be hereafter referred to as a block. Decomposition of a control system into multi-input blocks with just one output has practical significance, permitting a relatively rapid and simple translation of the control system component structure into a for readable for a microprocessor controller. Of course, technical limitations additionally restrict the permissible number of m - inputs. Each of the above defined blocks may be a component with:

- many inputs and one output
- many inputs without an output
- without inputs but with an output.

3. Transposition of control system block structure into machine readable form

Such transposition for efficient processing using a microprocessor controlled unit requires formal modeling of the system ,e.g. into records of data. A set of appropriately arranged records describing the block structure of a control system will hereinafter be referred to as a machine readable structure.

Each of the control system structural blocks may be described using a record containing the following indexed components:

- algorithms performed by the block
- algorithm parameters
- sources of input data
- value of output information.

The record consist of a fixed and variable part. The fixed part includes

- pointing to address of algorithm procedure performed by the block;
- pointing to constant values;
- pointing to sources of input information.

The variable part comprises:

- pointing to value of output information
- pointing to value of variable parameters.

4. Principles for formulation of a machine readable structure of a control system

A machine readable structure of the control system comprises a reproduction of the control system block structure in internal machine language. As processing of the structure and performance of algorithms pointed to by the appropriate variables describing the structure usually takes place sequentially and cyclically within the microprocessor controller, then adherence to appropriate relations and time regimes will require a transformation of the structure according to arranging principles. Such principles may be formulated in the following manner:

I. Each block scheme of a control system transformed into a format described by matrix (2) corresponds to exactly one machine readable block.

II. Blocks have unique numbers. The sequence of numbers described time sequence of performing algorithms assigned to the blocks.

III. The last machine readable block (highest numbered) ends the internal structure of control system.

IV. Processing of information in blocks to which algorithms are assigned is performed sequentially in cycles with a sampling regime adapted to the numbering of blocks. The repeat frequency of processing information encoded into rectors describing structure of the control system cannot be less than the maximum information processing time within individual structural blocks.

5. Flexible structure of control systems in a building machine

The above described control system block structure decomposition scheme with transposition of the structure into machine-readable form has been implemented within flexibly structured microprocessor control systems [3,6] designed for application in electro-hydraulic drives of building machines.

Application of the flexible structure was possible by writing an appropriate, problem oriented software systems for such controllers. Hence, it was necessary to develop[3]:

- a problem oriented interactive language (VALVIL); and

- high level graphical user software (CAVAL).

VALVIL describes a set of principles and methods for information interchange between the controller and external environment.

Structure of the language permitted to minimize the number of principles and methods applied, thus, facilitating apprehension of the language fundamentals by the operator, on one hand, and gave a compact and time-efficient program code for implementation in the microprocessor controller, on the other hand. The language permits both definition of the control system block structure, as well as its parametrization, i.e. allows the definition of an appropriately arranged sequence of records describing the structure and parameters of the control system. VALVIL as well as its interpreter are characterized by exceptionally time-efficient translation and performance of its commands. Hence, it allows quasi-dynamic changes of the control system structure and its parameters in many practical applications (adaptive systems). Its features include:

- programmed alteration of structure and parameters of the microprocessor controller of the system
- programmed control of a network of coupled controllers;
- programmed diagnostics of controller status
- performance of special functions related with the use of the controller and positioning of electro-hydraulic units.

CAVAL: is the graphical application software system supporting synthesis of control systems. Its use permits the direct user of microprocessor controlled units may perform configuring and parametrization of control systems without having in-depth knowledge of VALVIL language. The system has been designed in such a way which permits operation by inexperienced operators not having any knowledge of hardware or programming. However, the operator should have some experience in fundamentals of automation which are being referred to by CAVAL. The system performs functions similar to these of VALVIL and may be considered as its graphical environment. CAVAL consists of:

- block scheme editor

- block scheme translator

- direct communication with controller software.

Block scheme editor permits simple and convenient preparation of structure and parameters of control systems. An example of such a block structure has been given in fig. 1.

The translator is responsible for converting the defined structure into a set of VALVIL language commands. It includes a formal correctness verification of the defined structure. The listing of a translation of the structure given in Fig. 1 has been given in fig. 2.

Communication software permits direct transfer of the structure and parameters of a designed control system into the microprocessor controller.

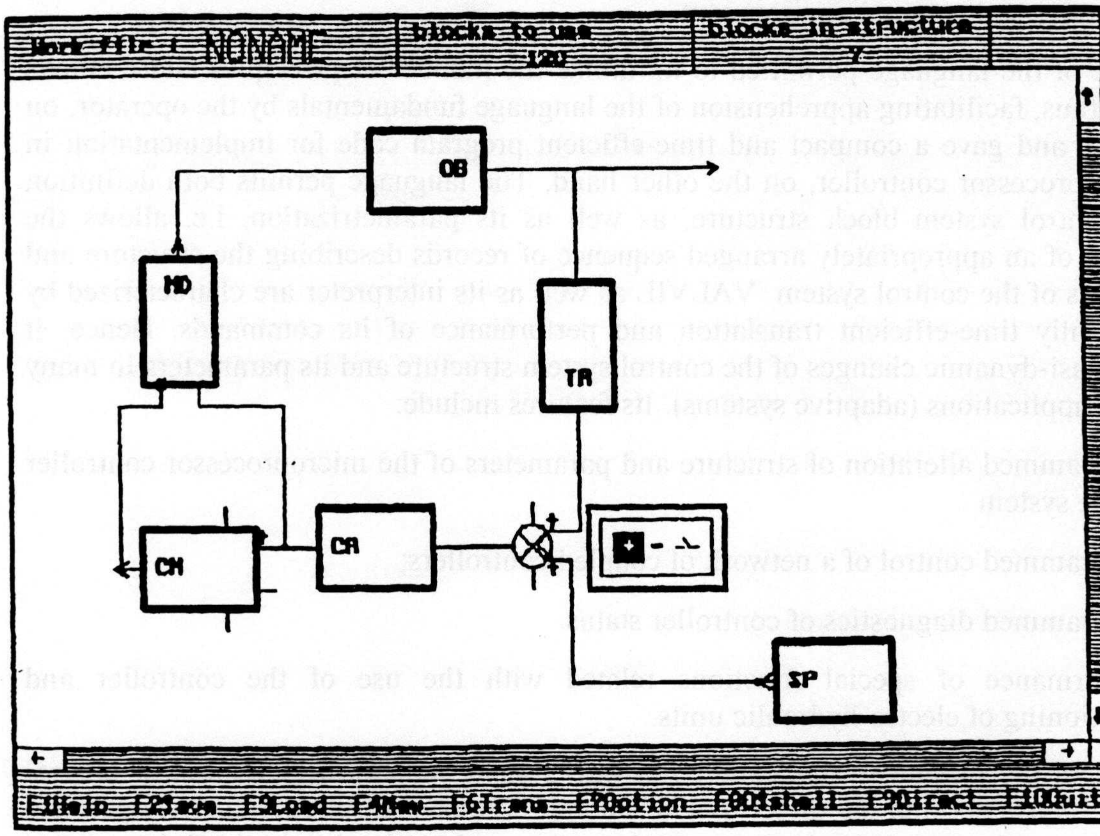


Fig. 1. A simple control system designed using CAVAL. OB - controlled object; TR - measuring transducer (piston rod position); SP - set value definer (shift); CR - controller; C - output value comparator; MD - two channel modulator of pulse width generating the set pulse and power step; S - summation node. The set value (lead)(is generated in real time and entered from an external, hierarchically superior control system through the SP interface which is the value defining unit. The output comprises piston rd shift of a servo motor measured by the programmed transducer TR.

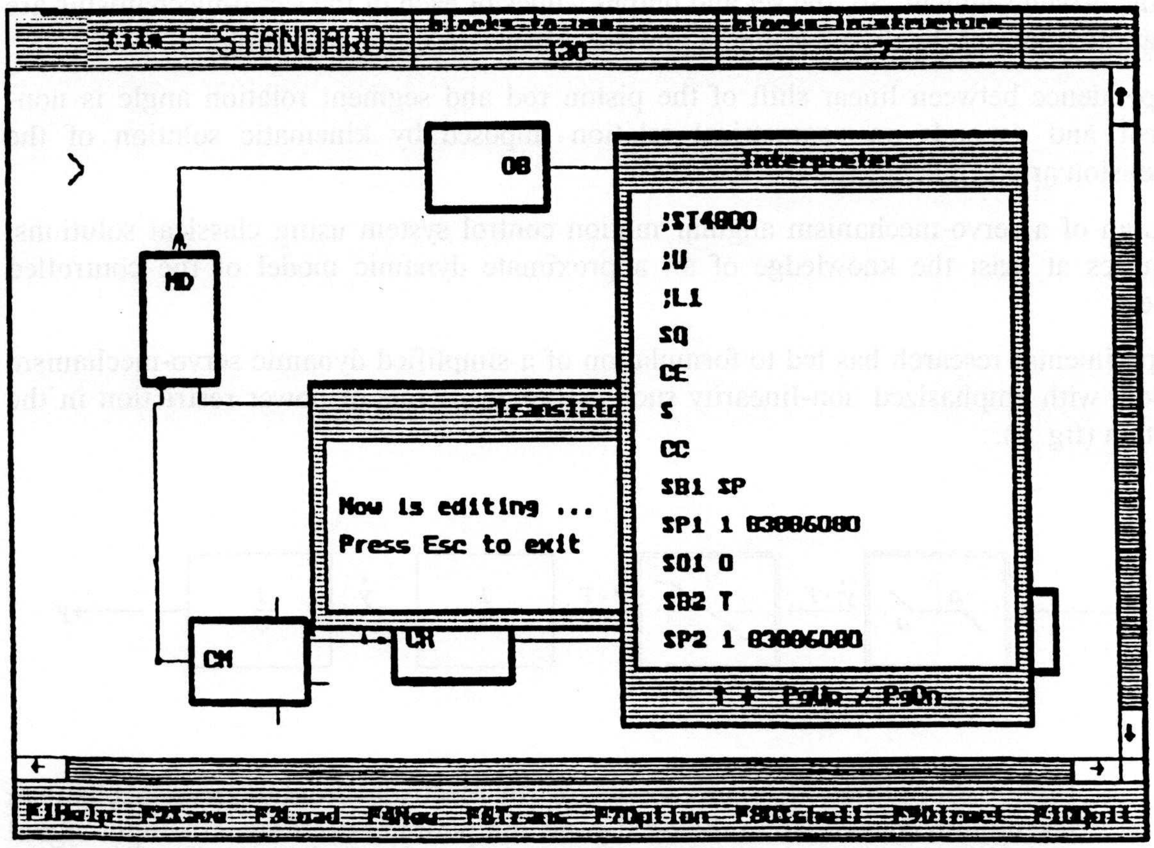


Fig. 2. Translation listing for the structure and parameters of the control system presented in Fig. 1. Abbreviations have the same meaning as given in Fig. 1.

6. Application of a control system in a servo motor drive of a concrete pump segment.

The central part of a microprocessor controller including the control system with programmable structure and parameters is typically general. Its application to control of electro-hydraulic drives used in machine construction requires inclusion of peripherals permitting direct mating of the controller with a switching or proportional electro-hydraulic manipulator.

A solution of this type conveniently integrates controlling and setting functions.

An example of applying a simple control system in a servo motor drive of one of the three segments of a concrete pump extension arm [5,7] will be presented below.

6.1. Simplified simulation mode of an electro-hydraulic servo-mechanism

The hydrostatic drive system of each of the three working segments of a concrete pump or hydraulic excavator is in each case an electro-hydraulic unit coupled with a linear hydraulic cylinder. Piston rod movement of a hydraulic servo is transformed into rotation of the driven segment. So, the set and output values of each of the servo-mechanisms are rotation angles of the driven segment and not direct shift of the piston rod.

Dependence between linear shift of the piston rod and segment rotation angle is non-linear and depends on geometrical relation imposed by kinematic solution of the extension arm segment [5].

Design of a servo-mechanism angular motion control system using classical solutions, requires at least the knowledge of an approximate dynamic model of the controlled object.

Experimental research has led to formulation of a simplified dynamic servo-mechanism model with emphasized non-linearity such as the dead zone or power restriction in the system (fig. 3).

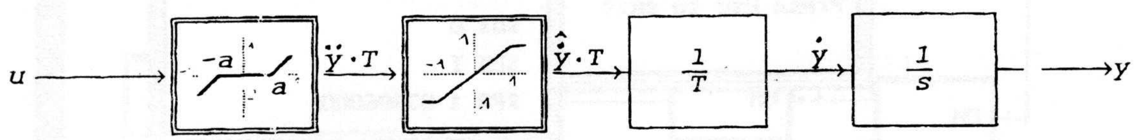


Fig. 3. Simplified dynamic model of an electro-hydraulic servo-mechanism taking into consideration the dead zone and power restrictions. u - input signal (setting value); 2a - width of dead zone; y - output signal (shift), T - time constant, A - dead zone block; B - power limitator; O - controlled object; S - summation node.

Existence of a **dead zone** is caused mainly by overlapping of mechanical and hydraulic systems of the electro-hydraulic manipulator..

The total width of the dead zone was experimentally determined for the W19 concrete pump extension arm at a = 37% (using Mannesmann-Rexroth manipulators) and defined as approximately symmetrical.

Since this form of non-linearity dominates, no consideration was given to in the approximate model of hysteresis caused by friction in the mechanical system or still more negligible elasticity hysteresis of materials and media in the servo-mechanism system.

Note that no practical solution permits the supply of unlimited power to the working unit. Therefore, the model assumes power restriction up to a certain maximum value which is independent of time and working position of the unit. This power supply restriction to the system affects maximum speed y and acceleration y of piston rod shift and limits the linear range of servo-mechanism operation when applying a proportional controller (see [34]).

Linearization of non-linear dead zone characteristics of the object is theoretically possible by introducing infinitively high gain in a closed control system. But, this is practically unacceptable. Instead, it is possible to consider correction of the non-linear static characteristics by introducing an opposite non-linear correction.

The use of such solution is desired for two reasons:

- it permits reducing of control deviation in stationary state without increasing gain of the system;
- it permits lower gain in the system when maintaining the same value of control deviation in stationary state.

However, in practice the exact width of the dead zone remains unknown and dependent on the configuration. Moreover, its width may be changed by non-stationary of construction and operating parameters which affect both size as well as symmetry. Therefore full compensation of the dead zone is both difficult and unnecessary. It may also lead to "over-correction", i.e. introduction of a non-linear correction to the linear part of the characteristics, which results in other types of non-linearity and generally increases energy losses.

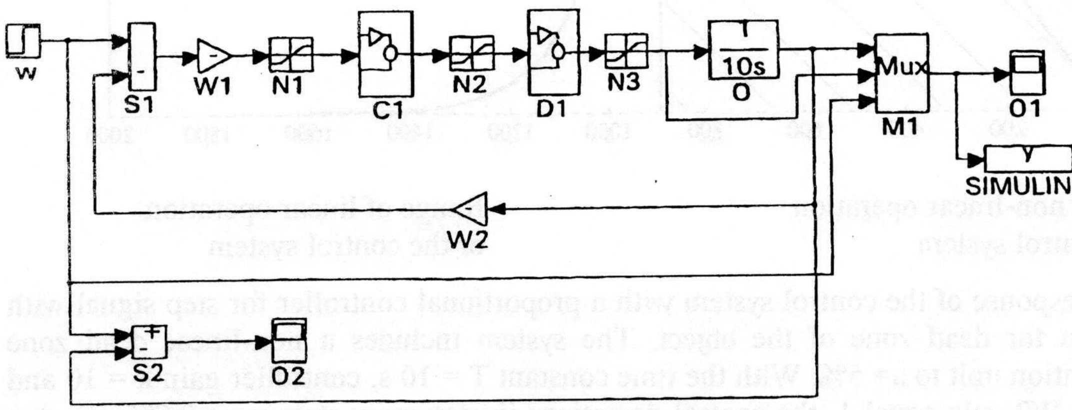
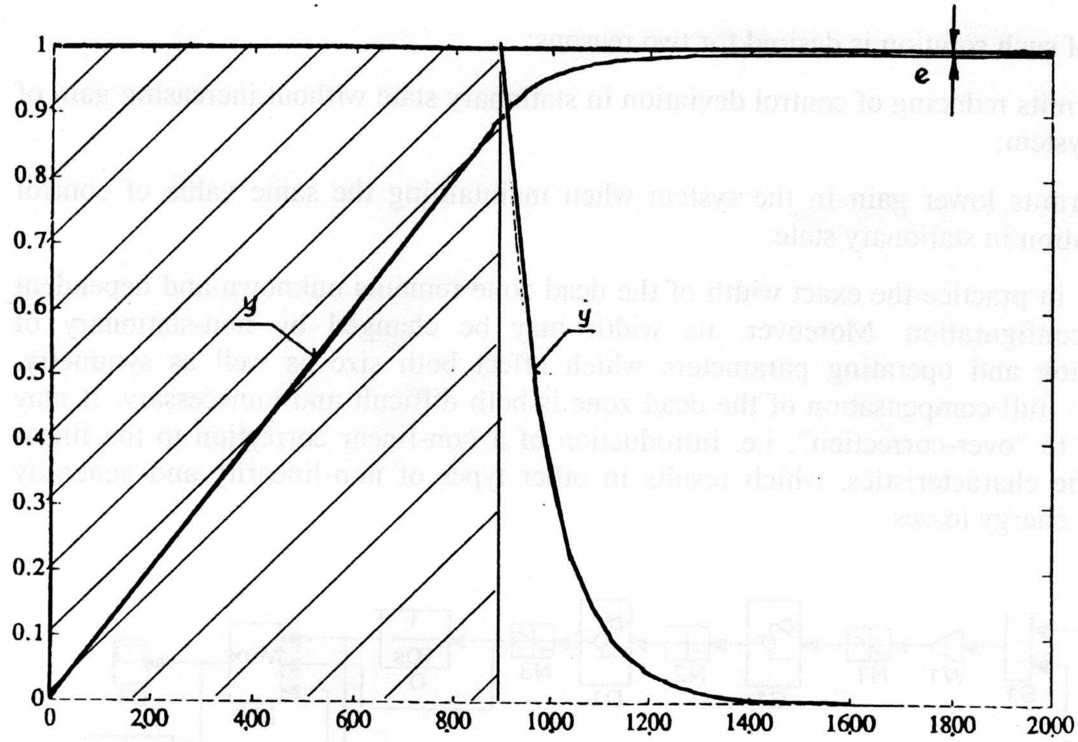


Fig. 4. Servo-mechanism simulation model for one of the segments of W19 concrete pump. w - unit stroke generator, S1 - summation node, W1 - proportional controller with gain k; N1 - unit restricting output signal of controller W1; C1 - dead zone correction unit; N2 - unit restricting output signal of correction unit C1; D1 - unit with dead zone; N3 - power limiter; O - transmittance of linear part of the object; M1 - multiplexer; O1 - y(t) recorder; y - output value vector; W2 - shift measurement (y) amplifier; S2 - summation node; O2 - e(t) recorder, e - control deviation.

The simulation model of the concrete pump extension arm electro-hydraulic servo-mechanism was prepared using tool software for simulation research (SIMULINK) under Windows 3.1. The simplified scheme presented in Fig. 4. includes both the above adopted model assumptions as well as certain practical limitations of implementations. In particular, this refers to the output signal limiters N1 and N2 which are integral components of all microprocessor controller structural blocks. The proportional controller was presented for simplicity. It is easily shown that the existing non-linearities which cannot be fully compensated make it practically impossible to assure zero deviation of control in stationary state even though the object has dynamic integrating properties (see example of simulation testing in Fig. 5).



Range of non-linear operation of the control system

Range of linear operation of the control system

Fig. 5. Response of the control system with a proportional controller for step signal with correction for dead zone of the object. The system includes a non-linear dead zone compensation unit to a= 5%. With the time constant T = 10 s, controller gain k = 10 and amplifier W2 gain equal 1, the control deviations in stationary state were 0.7%; y - step shift of servo motor; y - normalized speed of piston rod.

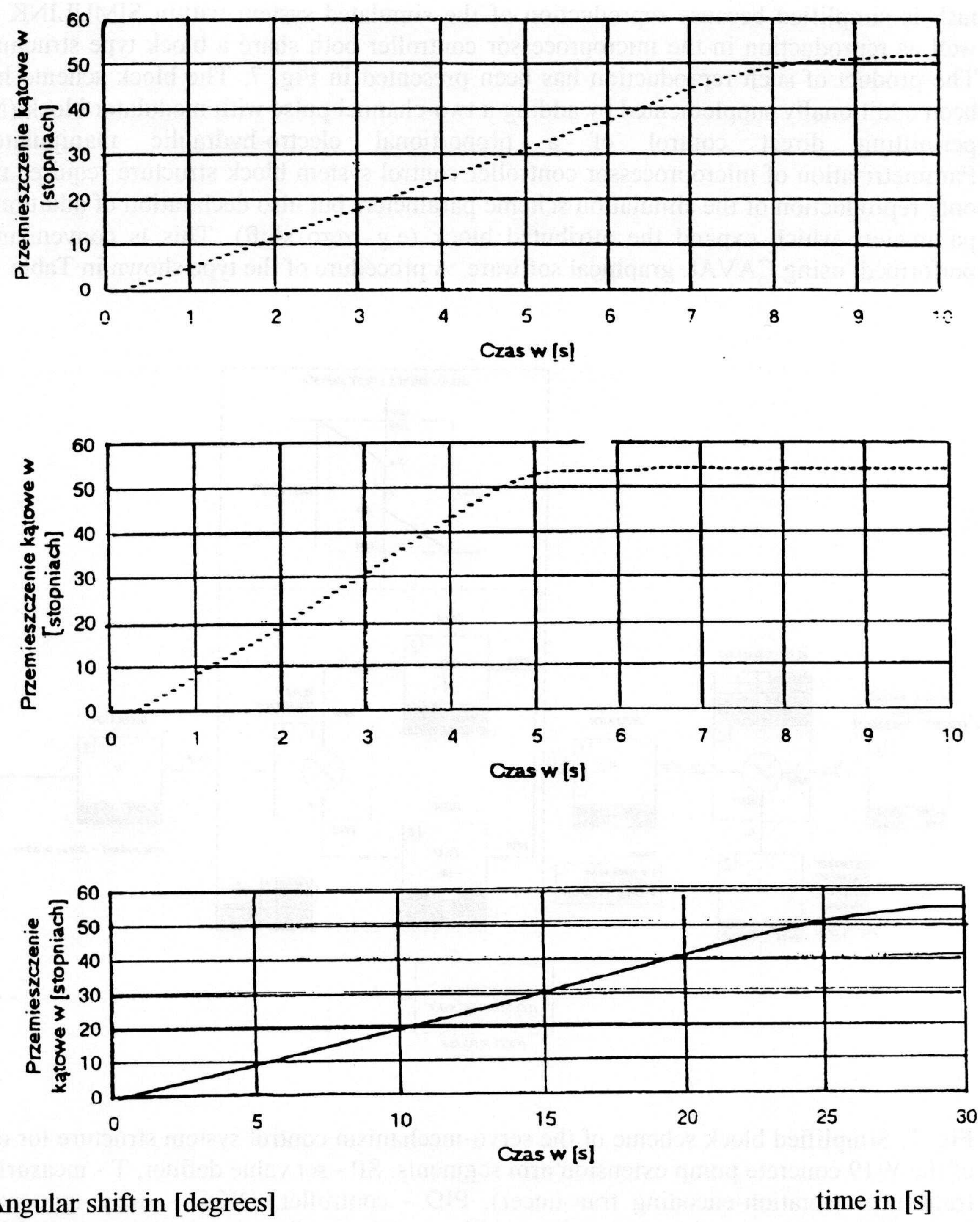
Simulation tests have shown that because of minimization of power loss in the system entry into linear operating mode should take place only during start-up and braking of the servo-mechanism. Those phases can be made aperiodical by appropriately defining the control system algorithm. Simulation and experiments (fig. 6) show that it is possible to use proportional regulators with dead zone non-linearity correction. It can be shown in such a case that the approximate value of control deviation in stationary state is given by [4]:

$$e = \left|\frac{a}{k}\right| \tag{3}$$

where:

a - effective width of dead zone after correction

k - gain coefficient in the control system.



Angular shift in [degrees] time in [s]

Fig. 6. Sample results of experimental responses to step (angular) pulses for servomechanisms of individual segments of W19 extension arm in automated control as for fig. 7 with upward stroke.

6.2. Implementation of the control system structure in the microprocessor controller

Implementation of a simulated control system in the microprocessor controller reduces transfer of its structure and parameters using VALVIL o CAVAL and takes under consideration special internal properties of the microprocessor controller system. The task is simplified because reproduction of the simulated system within SIMULINK as well as reproduction in the microprocessor controller both share a block type structure. The product of such reproduction has been presented in Fig. 7. The block scheme has been additionally supplemented by adding a two-channel pulse with modulator block (M) permitting direct control of a proportional electro-hydraulic manipulator. Parametrization of microprocessor controller control system block structure requires not only reproduction of the simulation scheme parameters but also declaration of additional parameters which expand the attributed block (e.g. zero shift). This is conveniently performed using CAVAL graphical software. A procedure of the type shown in Table 1.

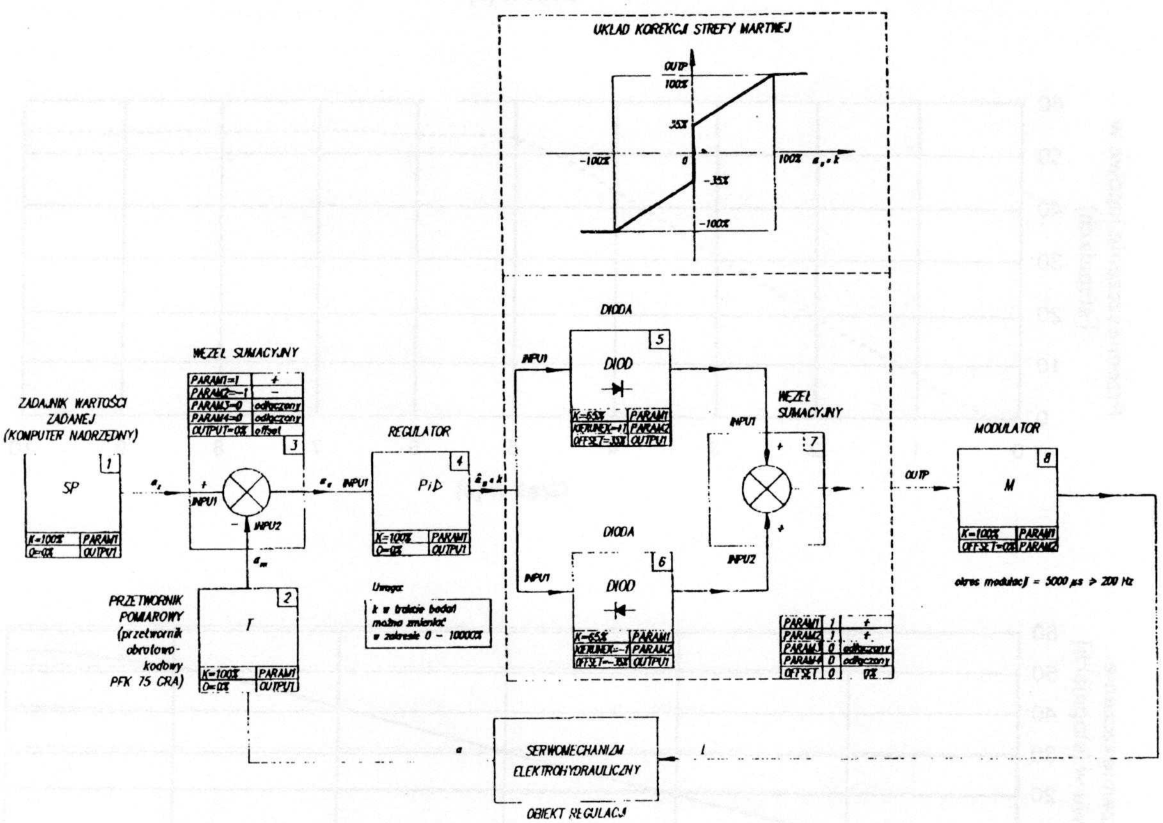


Fig. 7. Simplified block scheme of the servo-mechanism control system structure for one of the W19 concrete pump extension arm segments. SP - set value definer, T - measuring transducer (rotation-encoding transducer), PID - controller, DIOD - diode-type non-linear block; M - two-channel pulse width modulator; S - summation node; OB - controlled object, α, β, γ, I - signals in the control system.

7. Conclusions

The concept of a microprocessor control system with flexible structure and parameters, applied in electro-hydraulic unit positioning systems has been applied in practice [6, 7].

Table 1. Listing of the MB93 controller configuration program

```
;*************************************************************
;**              C O N T R O L     P R O G R A M            **
;**           FOR ONE ARM OF W19 CONCRETE PUMP              **
;**_________________________________________________________**
;**           Copyright:    Michal Bartys                   **
;**           TU-GH-Duisburg 26.01.1994                     **
;**_________________________________________________________**
;**              Made for IMBiGS Poland                     **
;*************************************************************
;**      P CONTROLLER  WITH NONLINEAR CORRECTION            **
;*************************************************************

;** Control phase   **

L
SA 4            ; Sets an address 4 !!
U
L4
SE
S
CC

;** Configuration phase  **

SB1,SP
SB2,T
SB3,S
SB4,P
SB5,DIOD
SB6,DIOD
SB7,S
SB8,M

SC1,3,1
SC2,3,2
SC3,4,1
SC4,5,1
SC4,6,1
SC5,7,1
SC6,7,2
SC7,8,1
;** Parametrisation phase  **
SP1,1,16777216
SZ1,0

SP2,1,16777216
SZ2,0

SP3,1,1
SP3,2,-1
SP3,3,0
SP3,4,0
SZ3,0

SP4,1,167772160
SZ4,0

SP5,1,10905190
SP5,2,1
SZ5,-5872026

SP6,1,10905190
SP6,2,-1
SZ6,-5872026

SP7,1,1
SP7,2,1
SP7,3,0
SP7,4,0
SZ7,0

SP8,1,16777216
SZ8,0

;** Initialization  **

I
C
```

The central unit of this system was built using two eight bit single chip microprocessors of the popular MCS-51 range from INTEL linked to a common RAM and EPROM. Each of the processors also has its own program memory. The processors operate in parallel with one having priority in access to the common memory base. The higher priority processor is the master while the lower priority one, is the slave. The distribution of tasks between both processors is as follows:

- the master processor performs controlling algorithms, transmission of information to and from the controller and emergency procedures;
- the slave processor performs pulse width modulation, operates the D/A converter, pules and code shift transducers, digital measurement of shift, speed and acceleration, digital filtration of measuring signals.

Clock speed of both processors is 12 MHz. This solution can be used for implement a control system of the type shown in Fig. 7 with sampling cycle of about 5 ms.

The concept of a control system which flexible structure and parameters is extremely useful, particularly in experimental research, where concept of the control system itself as well as of its parameters has to change according to results the obtained. Practical usefulness of the microprocessor controller has been confirmed at the instituted during analysis of the operation of W109 concrete pump extension arm and of the Warynski 711 hydraulic excavator. Results received so far point to the possible use of formal linguistic logic referring to heuristic knowledge in system controllers.

References

1. Hirsch U., Jacubasch A., Kuntze H., Eberle F., Goller B.: Modeling and Control of a Hydraulic Large Range Robot, pp. 609-620

2. Benckert H.: Computer Controlled Concrete Distribution, pp. 11-119.

3. Bartys M. Electro-hydraulic valves with digital input, Internal report A409, Institute of Industrial Automation, Warsaw University of Technology, Warsaw, 1990.

4. Bartys M.: Simulation testing of an electro-hydraulic servo-mechanism of the W19 concrete pump extension arm. Internal Report, IMBiGS, Warsaw, 1994.

5. Budny E.: Hydraulic systems of multi-segment working machines with elements of working movement automation. Scientific Library of Building Mechanization, IMBiGS. Warsaw 1994. p. 10 Lecture presented at the Scientific Conference on heavy Working Machines, January 1994.

6. Budny E., Bartys M.: System for controlling electro-hydraulic drive units of the W19 concrete pump extension arm. Internal Report, IMBiGS, Warsaw 1993.

7. Budny E., Bock T.: Excavator Rationalization by Hybrid Control System. Engineering. Construction and Operations in Space Conference, Albuquerque, New Mexico, February 26 - march, 1994. p. 9