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DYNAMIC MODELLING AND SIMULATION OF A HYDRAULIC STEPPER CYLINDER USED IN MANIPULATORS AND ROBOTS

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Abstract: The present paper describes dynamic modelling, results of simulation and experimental investigation of a hydraulic stepper cylinder, which find application in manipulators and robots. The method of bond graph is used for modelling of the dynamics of the considered cylinder design. First, an initial digital simulation is performed in order to calculate basic dynamic characteristics of the cylinder. Next, an additional damping system is applied which affects dynamic characteristics of the considered cylinder. Finally, results the model simulation are verified experimentally

Keywords: Hydraulic stepper cylinder, dynamic modelling, digital simulation, bond graph method.

1. INTRODUCTION

Hydraulic stepper cylinders make it possible to obtain some precisely definite positions of piston. These cylinders find application in moving ports of industrial manipulators and robots or they can perform auxiliary functions in the drives of technological machines. Examples of different hydraulic stepper cylinders are presented among others in works [6], [8], [9]. Stepper cylinders have to satisfy such requirements, as high reliability and speed, precision of performance, irrespective of the properties of working fluid and the rate of piston movement. The technique of the control of a stepper cylinder presented in this paper is similar to the application of hydraulic stepper motors and is classified as so-called track program control [7]. This control consists in the fact that one of the ports of the cylinder is connected with a return line to the tank. The piston moves in the desired direction to reach the point precisely opposite this port. In steady state pressure on both sides of the piston is equalized, and fluid flows through uniform holes to the tank. In order to secure proper dynamic properties of the stepper cylinder an additional damping is introduced. Schematic representation of a hydraulic stepper cylinder is presented on Fig.1a. Bond graphs [1], [2]. [3], [5] are used for modelling of the dynamics of the stepper cylinder. In selecting a method of dynamics modelling it is taken into consideration that the dynamic structure of bond graphs is closely identifiable with the functional structure of the hydraulic system. As accumulation of kinematic and potential energies on bond graphs are described by means of time function these graphs are applicable to digital simulation.

2. DESIGN SOLUTION AND DYNAMIC MODELLING OF THE STEPPER CYLINDER

In the adopted design of a hydraulic stepper cylinder, presented in a simplified way on Fig.1b, four positions of the piston are obtained. The stepper cylinder is fed from the source of constant pressure. In the inlets to the right and left chambers of the cylinder throttle valves (the capillary and orifice type) of constant diameter are fixed. In the cylinder a sleeve with properly made grooves and holes is fixed. Turning the sleeve by angles 0 and 180 one obtains positions 1 and 3. Turning it by angles 90 and 270 positions 2 and 4 are obtained. In each position of the piston the cylinder is connected with the return line to the tank through four holes. The piston assumes left position 1 or 2 when control shutoff valve I is open and control shutoff valve II is closed, and it assumes right position 3 or 4 when the control shutoff valve I is closed and control shutoff valve II is open. For example, opening of the control shutoff valve I and closing of the shutoff valve II cause decrease of pressure p_1 and quick displacement of the piston from the right to the left position. As the result of volume increase in chamber 1 and volume decrease in chamber 2 pressure p_1 increases and pressure p_2 decreases. The pressure in the left and right chambers of the cylinder increases and decreases alternately until the steady position of the piston is achieved. The piston position is established after achieving equilibrium state of forces acting on the cylinder piston.

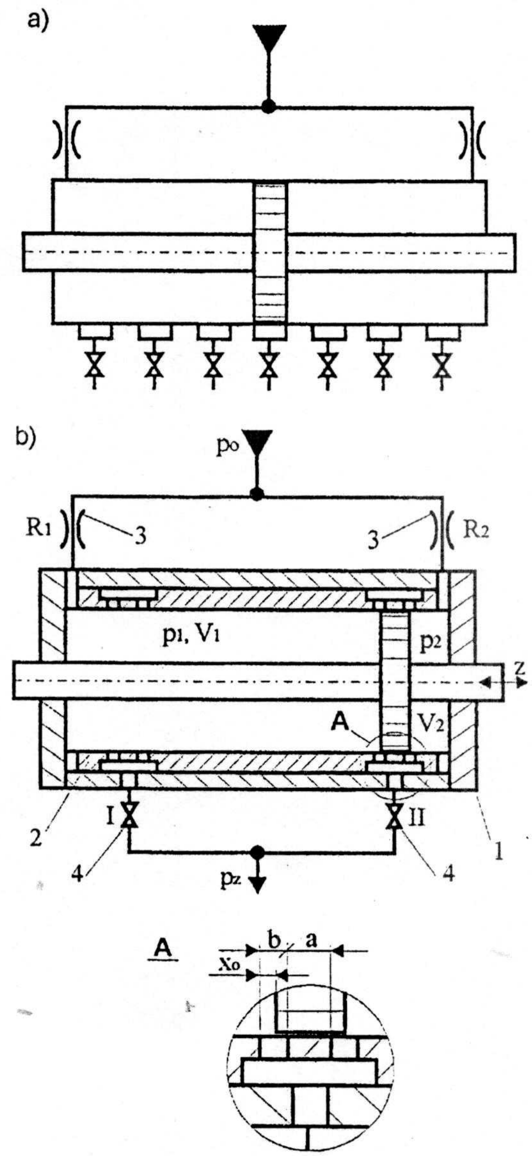

Figure 1. Hydraulic stepper cylinder: a) schematic representation, b) experimental model, 1 - cylinder, 2 - sleeve, 3- throttle valves, 4 - control shutoff valves

In modelling of the dynamics of a stepper cylinder the following simplifying assumptions have been adopted: discharge pressure p_o is constant (p_o = const), pressure p_z in the outlet line to the tank corresponds to atmospheric pressure (it can also be written that $p_z = 0$), the temperature change ΔT of working fluid has little influence on the cylinder characteristics (then it can be assumed that T = const), density ρ and bulk modulus E_c of working fluid do not depend on temperature and pressure (ρ = const, E_c = const). Under the change of piston position cavitation does not occur, internal leaks in cylinder are negligible due to small difference of pressure on both sides of the piston, pressure losses and fluid compressibility do not occur in supply lines. The method of bond graphs is used for modelling of dynamics of a stepper cylinder. In order to obtain positions from the cylinder position integrator *INT* is additionally introduced. In creating a bond graph of the cylinder the following denotations are introduced: SE_p - energy effort source which corresponds to pressure p_o, SE_c - effort source which corresponds to Coulomb friction, C_1, C_2 - hydraulic capacitances in cylinder chambers, A - piston area, TF - transformer of hydraulic energy into mechanic energy, I - inertance which corresponds to masses of piston and external loads, R_1, R_2 - hydraulic resistances of throttle valves, R_v - resistance corresponding to viscotic friction between piston and cylinder barrel, proportional to piston velocity v, R_{11}, R_{12} R_{21}, R_{22} - hydraulic resistances dependent on variable flow slots between piston and cylinder sleeve. These resistances correspond to flow rates: $Q_{11}(R_{11})$, $Q_{12}(R_{12})$, $Q_{21}(R_{21})$ and $Q_{22}(R_{22})$ which depend on the position of cylinder piston [3]. A general formula for flow rate through flow slots between cylinder piston and sleeve can be written as follows:

$$Q_{ij} = \mu\, A_{ij}(x) \sqrt{\frac{2}{\rho}\left(p_i - p_z\right)} \tag{1}$$

where: μ - coefficient of flow rate, A_{ij} - area of flow section from the i-th cylinder chamber to the j-th outlet slots, x - opening of outlet slots, p_i - pressure in the i-th cylinder chamber, p_z - pressure in the outlet line to the tank.

The dependence of flow section A_{ij} on opening x of outlet slots 1 and 2 is represented on static characteristics on Fig.2.

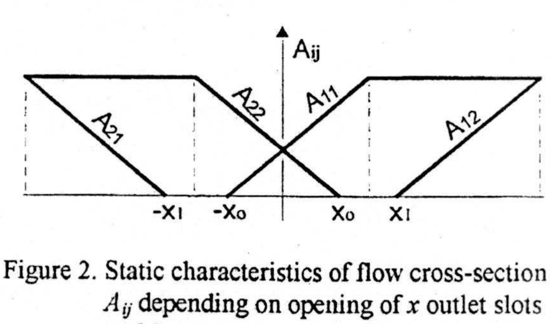

Figure 2. Static characteristics of flow cross-section A_{ij} depending on opening of x outlet slots 1 and 2

The bond graph of a hydraulic stepper cylinder, for previously determined parameters, is represented on Fig.3.

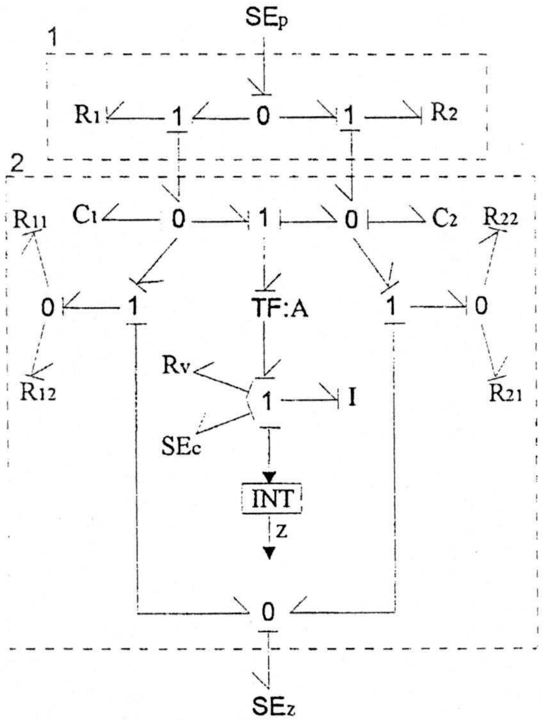

Figure 3. Bond graph of dynamic model of stepper cylinder: 1 - throttle valves, 2 - cylinder

After analysing the created model of the dynamic stepper cylinder it has been decided to extend it by conduits between throttle valves and cylinder. Such extension is justified by the fact that conduits can have significant lengths. The phenomena which occur during damping of piston vibrations and are accompanied by return flow to conduits should be also taken into consideration. In the extended dynamic model the following parameters of conduits will be taken into account: C_{l1} and C_{l2} - hydraulic capacitances, I_{l1} and I_{l2} - hydraulic inertances, R_{l1} and R_{l2} - hydraulic resistances. The bond graph of such an extended model of the dynamic stepper cylinder is represented on Fig.4.

The dynamic characteristics of a stepper cylinder can be determined by the method of digital simulation on the basis of the dynamic model represented by means of bond graph, using one of the available simulation programs, e.g. CSSL. In digital simulation the following parameter values were introduced:

$A = 0.77\ 10^{-3}\ m^2$, $I = 12$ kg, $SE_c = 100$ N,

$p_o = 15$ MPa, $R_1 = R_2 = 0.41\ 10^9$ Pas/m^3,

$\eta = 0{,}062$ Pas, $E_c = 895$ MPa,

$C_1 = C_2 = 0.85\ 10^{14} \div 0.42\ 10^{-13}$ m^3/Pa,

$\rho = 850$ kg/m , $I_{l1} = I_{l2} = 1.1$ MPas^2/m^5 ,

$C_{l1} = C_{l2} = 0.8\ 10^{-14}$ m^3/Pa,

$R_{l1} = R_{l2} = 1.28\ 10^9$ Pas/m^3.

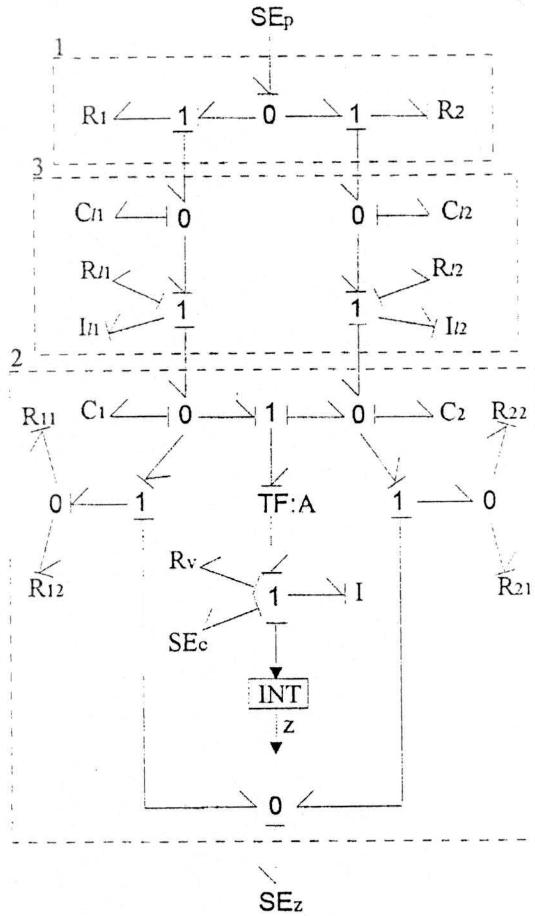

Figure 4. Bond graph of extended dynamic model of stepper cylinder: 1 - throttle valves, 2- cylinder, 3 - supply conduits

After reverse control of shutoff valves I and II, when the cylinder piston changes its position dynamic characteristics are determined to show runs of pressure difference $p_1(t) - p_2(t)$ in cylinder chambers, displacements $z(t)$ and velocities $v(t)$ of cylinder piston. The exemplary dynamic characteristics are presented on Fig.5. Requirements for a stepper cylinder involve a high precision of piston positioning and strong and possibly short-time damping of its vibrations.

3. DYNAMIC MODELLING AND INVESTIGATION OF A STEPPER CYLINDER WITH DAMPER

In order to obtain the required dynamic properties of the hydraulic stepper cylinder an additional damping system (damper) has been introduced to its control system. The diagram of the stepper cylinder with a hydraulic damper is represented on Fig.6.

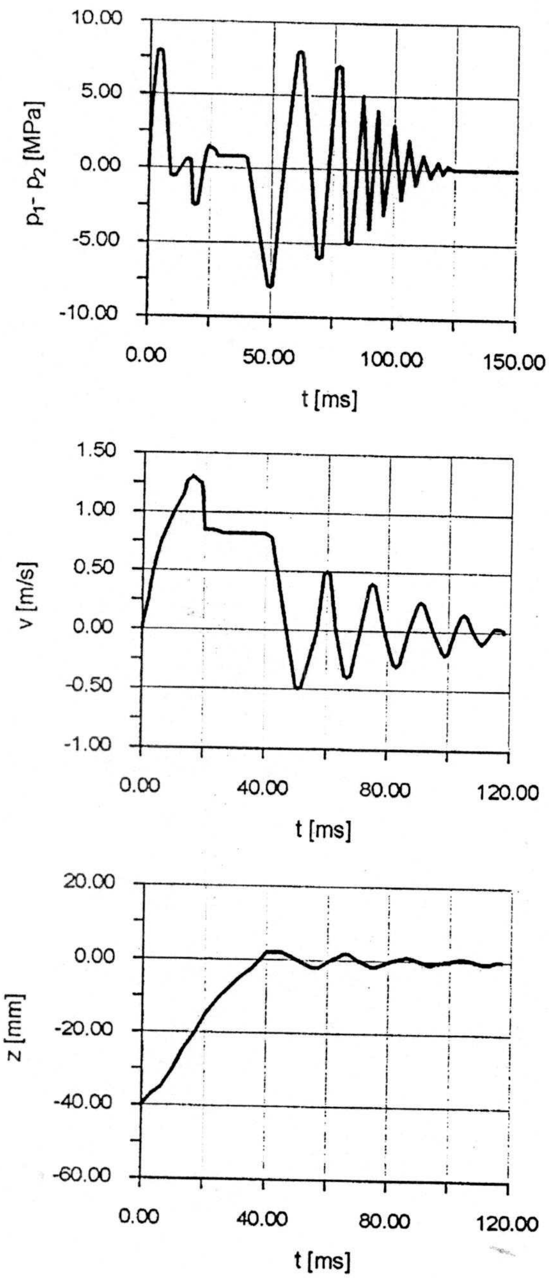

Figure 5. Dynamic characteristics of stepper cylinder

The adopted damper has a design solution applicable in hydraulic cylinder [1]. This damper consists of a damping valve which performs the function of the bypass valve between two cylinder chambers, four return valves and an accumulator. In steady state the damping valve is closed. Thanks to application of return valves the damping valve acts depending on higher pressure in a given cylinder chamber. The damping valve opens when the force resulting from pressure difference p_{t1} and p_{t2} is higher than the force of spring action. The accumulator performs the function of a pressure vessel in the damper.

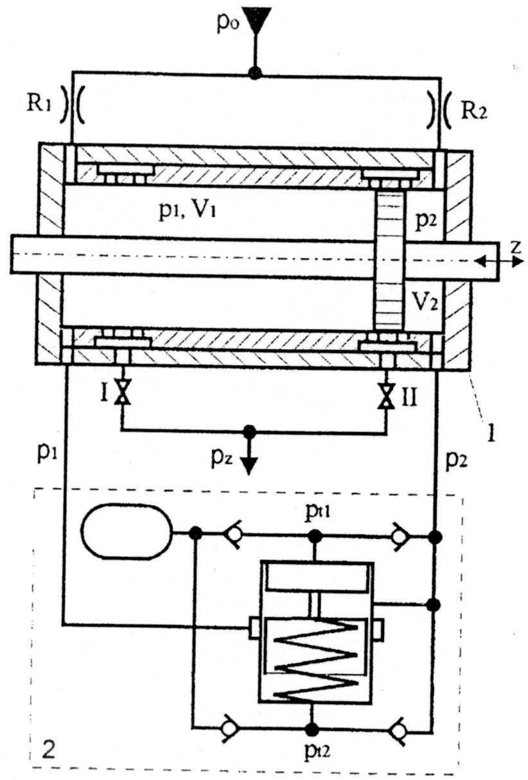

Figure 6. Diagram of stepper cylinder with damper: 1 - cylinder, 2 - damper

After damping valve has been opened an additional fluid flow occurs between the two cylinder chambers. It is responsible for the damping effect of pressure pulsation caused by change of the position of the cylinder piston. The damper has a favourable effect on the run of dynamic characteristics of the cylinder but it can also contribute to energy losses and stepper errors. The design of the damping valve with a spool decreases the unfavorable influence of the damper on the accuracy of positioning of the cylinder piston. Fluid compressibility in the area of the damping valve, due to small volumes, is negligible. Inside the valve spool a damping passage is fixed. While creating a bond graph of the damper we introduced hydraulic resistances R_{td} and R_{ty} which correspond to resistances of fluid flow through damping passage and a flow slot of the spool valve, as well as resistances R_{tv} and R_{th} of viscotic friction and hydrodynamic force of fluid flow through a spool valve. Besides, we introduced inertance (mass) I_t of the spool, area A_t of the spool, force of spring action of mechanical capacitance (compliance) C_s, hydraulic capacitance C_a and hydraulic resistance R_a of the accumulator orifice plug. In the bond graph of the damper such elements as: transformer *TF*, modulated transformer *MTF*, function generators *FNC*, integration component *INT* and multiplication component *MUL* are also included. In creating the bond graph of the damper the dependence describing pressure difference in the spool valve is taken into consideration. It can be expressed as follows:

$$p_{t1} - p_{t2} = \left| p_a - p_2 \right| \tag{2}$$

A bond graph of stepper cylinder with a damper is represented on Fig.7.

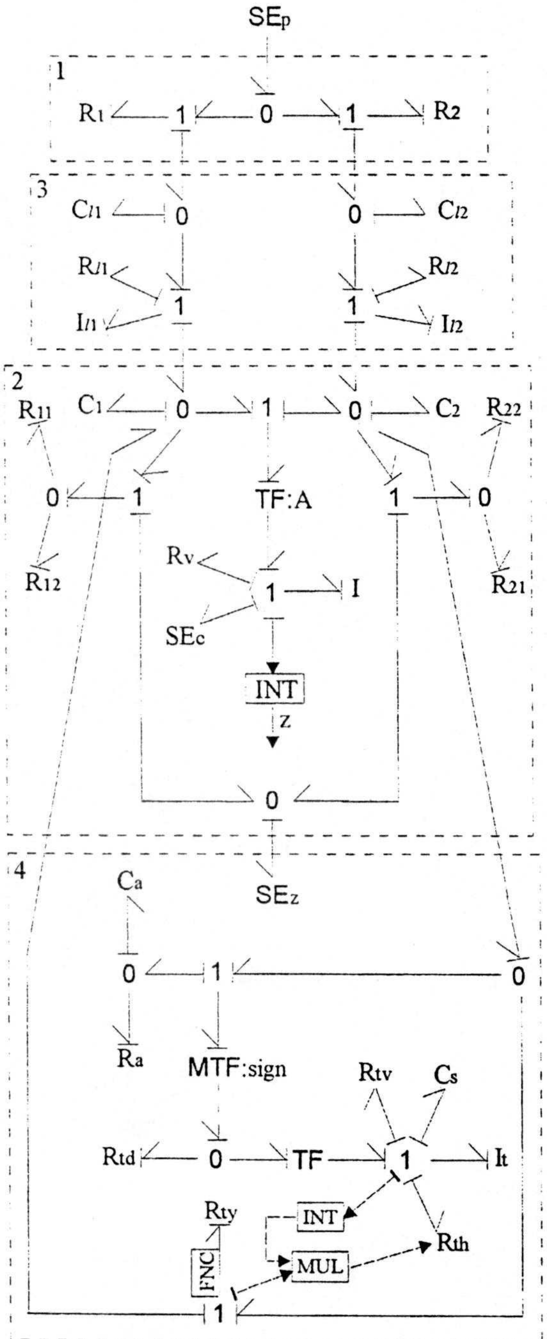

Figure 7. Bond graph of stepper cylinder with damper: 1 - throttle valves, 2 - cylinder, 3 - supply conduits, 4 - damper

Where flow rate Q_{ty} and hydrodynamic force F_{th} (resulting from this flow) are denoted symbolically by means of resistance R_{ty} and R_{th}. The dynamic model of a stepper cylinder with a damper, defined by has been completed on the basis of the bond graph from Fig.7. Once the damper has introducted, the digital simulation of stepper cylinder is performed under the same initial conditions as those used for a stepper cylinder without damper. The obtained dynamic runs including: pressure difference $p_1(t) - p_2(t)$ in the cylinder chambers, displacement $z(t)$ and velocities $v(t)$ of the cylinder piston are shown on Fig.8.

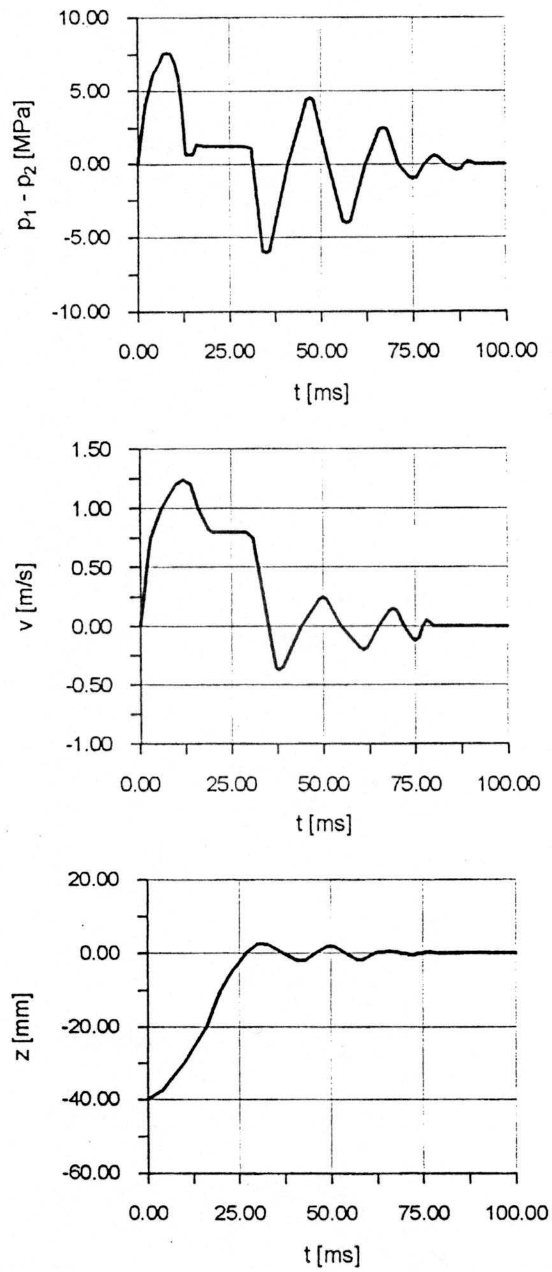

Figure 8. Dynamic characteristics of stepper cylinder with damper

For the estimation of the dynamic properties of the stepper cylinder the following quality factors are assumed: δ_p - overshot, t_p - stepper setting time, T - time constant, δ_o - oscillation and $|\Delta z|$ - position deviation which are described, among others, in the paper [4]. On the basis of the dynamic characteristics presented on Figs.5 and 8 the quality factors of stepper cylinders with damper and without damper are determined. The following values of quality factors were obtained for a stepper cylinder without damper: $\delta_p = 5$ %, $t_p = 90$ ms, $T = 33$ ms, $\delta_o = 75$ %, $|\Delta z| = 1.2$ mm. And the following values of quality factors are obtained for a cylinder with damper: $\delta_p = 7.5$ %, $t_p = 65$ ms, $T = 26$ ms, $\delta_o = 50$ %, $|\Delta z| = 0.7$ mm. By comparing the above quality factors it can be stated that improvement was obtained for a cylinder with damper in relation to time constant T, stepper setting time t_p, oscillation δ_o and position deviation $|\Delta z|$. However, increase in overshot δ_p of this cylinder can be accounted for by an increase in damping coefficient after the introduction of damper. On the basis of the performed investigation it can be stated that the design solution of the damper is selected correctly and accuracy of the cylinder positioning is within admissible 5 % deviation, i.e. $|\Delta z| \leq 0.05\, z_o$ (where z_o is the travel of positioning piston, in this case $z_o = 40$ mm). The results of digital simulation are verified experimentally. The exemplary dynamic characteristics which represent runs of displacement *z(t)* of the cylinder piston obtained during simulation and experimental investigations are presented on Fig.9.

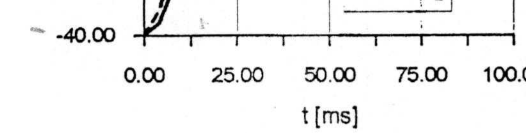

Figure 9. Comparison of the dynamic characteristics of stepper cylinder with damper:
1 - simulation, 2 - experimental

The convergence of the simulation and experimental results is the evidence of a correct adoption and properly selected parameters of a hydraulic stepper cylinder with damper.

4. CONCLUSIONS

1. The design solution of a hydraulic stepper cylinder presented in this paper allows to obtain many different positions of piston by exchanging the sleeve with properly made outlet slots.
2. Bond graphs, applicable to digital simulation, are used to modelling of the dynamics of a hydraulic stepper cylinder.
3. The dynamic model of a stepper cylinder has been extended by supply conduits and additional damping system (damper).
4. The initial simulation investigation of a stepper cylinder showed that for improving its dynamic characteristics additional damping should be applied.
5. It results from the dynamic characteristics of a stepper cylinder that change of the position of the piston of a cylinder with damper occurs in a shorter time and under well attenuated vibrations.
6. The dynamic properties of a hydraulic stepper cylinder with damper are confirmed experimentally.

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