24th International Conference
ENGINEERING MECHANICS 2018
Svratka, Czech Republic, May 14 –17, 2018
Paper #43, pp. 185–188, doi: 10.21495/91-8-185

SENSORLESS POSITION CONTROL SYSTEM OF HYDRAULIC LINEAR STEPPER ACTUATOR

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Abstract: *The paper discusses a sensorless position control system based on the applied principles of the digital hydraulic system (DHS). In the paper presents a design and working principle of a sensorless position control system whose hydraulic linear stepper actuator is controlled by a combination of single binary on/off valves. The dynamic model and digital simulation results of a design of sensorless position control of the hydraulic linear stepper actuator are presents. For this purpose, the bond graph method representing the functional structure of the hydraulic positioning system was used. Preliminary simulation tests were conducted to determine the basic dynamic characteristics of the hydraulic linear stepper actuator. The dynamic properties of the hydraulic linear stepper actuator were estimated.*

Keywords: model of hydraulic linear stepper actuator, bond graph method

1. Introduction

In Figure 1, a general operating diagram of the sensorless position control system of the hydraulic linear stepper actuator controlled by means of a combination of individual binary on/off valves is shown. To move the actuator piston from any initial position to *i*-th position, the binary valve V_i should be switched from OFF to ON state. When the binary on/off valve V_i is opened, the actuator piston moves at the outflow slots. The actuator piston stops at the place where hydraulic fluid flows out from the actuator chamber through the binary valve V_i into the tank. The steady state, i.e., the precision position of the hydraulic linear stepper actuator for a given step, will be achieved after the pressures p_1 and p_2 in the actuator chambers have equalized.

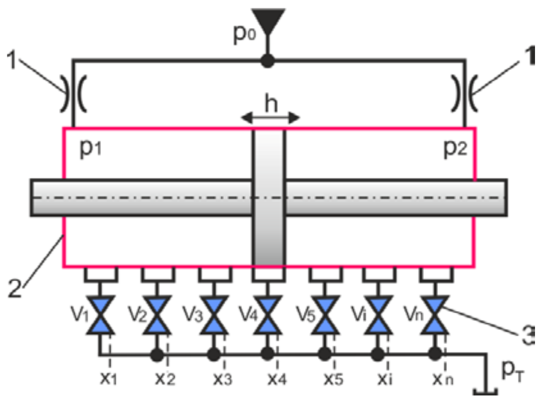

Fig. 1. The general operating diagram of the sensorless position control system of hydraulic linear stepper actuator:1 – throtlle valves, 2– multi stepper actuator, 3 – binary on/off valves

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The hydraulic linear stepper actuator is positioned in equal *n*-steps depending on the opening of one binary on/off valve V_i (V_1-V_n). The binary valves have only two states, that is, ON state (binary 1) or OFF state (binary 0). For the OFF state, the control signal is $x_i = 0$ (voltage 0 V) and the solenoid actuated valve V_i is closed. For the ON state, the control signal is $x_i = 1$ (voltage 24 V) and the solenoid acted valve V_i is open. The control equation for the combination of individual binary on/off valves V_i can be written as follows:

$$PV = \sum_{i=1}^{n} V_i\, x_i = V_1\, x_1 + \cdots + V_n\, x_n \qquad (1)$$

And, the *i*-the position (stroke) of the actuator piston can be determined as follows:

$$h_i = h_x + (i - x)\, \Delta h \quad \text{for} \quad i = 1, \dots, n \qquad (2)$$

where: h_x, Δh – starting position and step length of the actuator piston.

2. Model of sensorless position control system of hydraulic linear stepper actuator

Figure 2 presents a solution of sensorless position control system, which consists of the hydraulic linear stepper (with equal *n* steps) actuator, two throttle valves and *n* binary on/off (2/2-way seat) valves controlled electromagnetically.

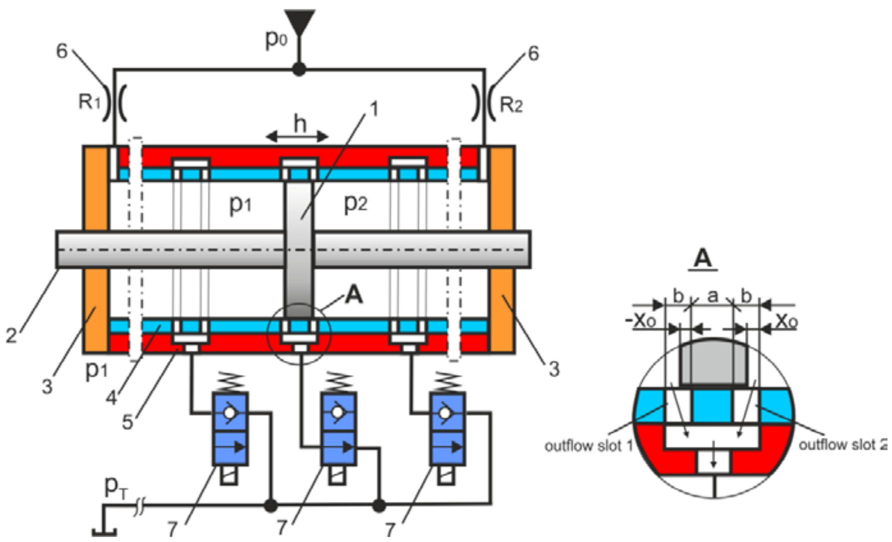

Fig. 2. Solution of sensorless position control system of hydraulic linear stepper actuator: 1 – piston, 2 - piston rod, 3 – cylinder caps and, 4 – cylinder sleeve, 5 – cylinder, 6 – throttle valves, 7 – binary on/off valves

The hydraulic linear stepper actuator is supplied from a hydraulic constant pressure source p_0 =const representing an ideal source of hydraulic energy regardless of the flow rate. Two identical non-adjustable throttle valves are placed at the inlet of the right and left side of the actuator chamber. At the outlet of the hydraulic linear stepper actuator there are *n* binary on/off valves. The binary on/off (poppet-type) valves are similar to pilot-to-open check valves, but they work like bleed valves. As shown in the hydraulic diagram in Figure 2, the binary valve bleeds the flow in the ON state and stops the flow in the OFF state. The binary on/off valve is actuated by solenoid coil and returns to the starting position due to spring action. After turning on the power supply of the solenoid, the binary valve immediately opens the flow path from the outflow slots to the tank. In the case of a higt speed on/off selenoid valve, this means switching delay time 5-20 ms. On the other hand, the on/off poppet valve opens as much as the flow going through it needs. The poppet has less distance to move to stop flow, thus its response is faster than that of other valves (i.e. spool valves). After opening of the *i*-th binary on/off valve there is a pressure drop in one cylinder chamber. As a result of pressure difference $\Delta p = |p_1\text{-}p_2|$, the actuator piston moves to the place of flow through outflow slots 1 and 2. The actuator piston moves until the steady state in which there is a balance of forces acting on the actuator's piston, when the pressure p_1 in the left chamber and p_2 in the right chamber are the same is reached. The pressures (p_1 and p_2) in the left and right actuator chambers can alternately increase and decrease until the condition of the steady state of the piston is satisfied. Outflow slots 1 and 2 with the actuator piston create symmetrical metering edge with negative overlap, as detail A in Figure 2 shows.

3. Bond graph modelling of sensorless position control system of hydraulic linear stepper actuator

The method of Bond Graphs strictly identified with the functional structure of the hydraulic positioning control systems is used for dynamic modelling of a sensorless position control system of a hydraulic linear stepper actuator. According to the definition the bond graph represents an instantaneous energy flow, i.e., power between power ports of different bond graph nodes (Thoma, 1990). The power transferred equals the product of two physical quantities, which are called effort *e* and flow *f*. Since the equations of kinematic and potential energy on bond graphs are described by means of time function the bond graphs are applicable to digital simulation. For the creation of a bond graph modelling of the hydraulic linear stepper actuator the following denotations were introduced: SE_p - energy effort source which corresponds to pressure $p_{0;}$ SE_c - effort source which corresponds to Coulomb friction; C_1, C_2 - hydraulic capacitances in actuator chambers; *A* - piston area; *I* - inertance which corresponds to the mass of piston and external mass loads; R_1, R_2 - hydraulic resistances of throttle valves; R_v - resistance corresponding to viscotic friction proportional to piston velocity v; R_{11}, R_{12}, R_{21}, R_{22} - hydraulic resistances dependent on variable flow rate between actuator chambers (1, 2) and outflow slots (1, 2): $q_{v11}(R_{11})$, $q_{v12}(R_{12})$, $q_{v21}(R_{21})$. In the bond graph such elements as: transformer *TF*, modulated transformer *MTF*, integration component *INT*, function blocks *FNC* and multiplication block *MUL* are included. Transformer element *TF* is a two-port bond graph element transforming energy from one domain into another. *TF:A* transforms hydraulic power into mechanical power. Modulated transformer element *MTF* is not constant, but depends on time or any other parameter. In order to obtain piston stroke *h* the integrator component *INT* is introduced. The *FNC* blocks are used for a non-linear function with one variable and the *MUL* block for a non-linear function with several variables. The *FNC*1 and *FNC*2 blocks represent flow rate through the throttle valves at the actuator inlet. The *FNC*3 block represent flow rate through the on/off valve at the actuator outlet. The *FNC*4 block represent flow resistances in the damper valve. In the papers (Dindorf, 1999) the bond graph model of a hydraulic stepper cylinder was extended by supply conduits. A bond graph model of sensorless hydraulic positioning system is represented on Figure 3.

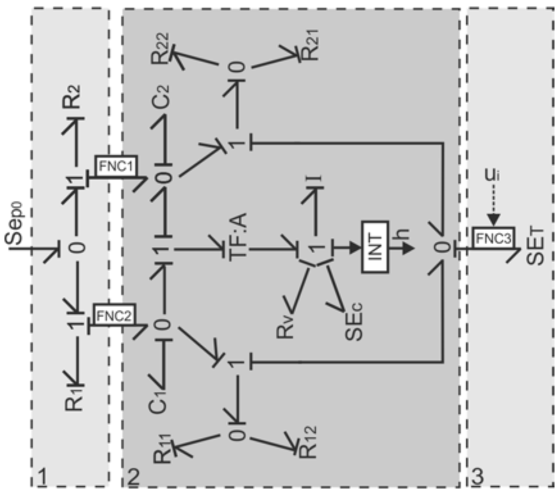

Fig. 3. Bond graph model of sensorless hydraulic positioning system: 1 - throttle valves, 2 - hydraulic linear stepper actuator, 3 - on/off control valve

4. Simulation results of sensorless position control system of hydraulic linear stepper actuator

The dynamic characteristics of a sensorless position control system of hydraulic linear stepper actuator was determined on the basis of the dynamic model represented by means of bond graph method (Dindorf et. al., 2016). The digital simulation was carried out using the available software, i.e. CAMPG (Computer

Aided Modelling Program with Graphical Input) with interface to Matlab/Simulink (Borutzky, 2011). In digital simulation the following basic parameter values were introduced: SE_p = 15 MPa, SE_c = 100 N, $A = 0.77\ 10^{-3}$ m^2, I = 12 kg, $R_1 = R_2 = 0.41\ 10^9$ Pas/m^3, $C_1 = 0.85\ 10^{14}$, $C_2 = 0.42\ 10^{-13}$ m^3/Pa. On the basis of the bond graph model from Figure 3 and the digital simulation using CAMPG the dynamic characteristics of the hydraulic linear stepper actuator during step positioning were determined. The example of dynamic characteristics of a hydraulic linear actuator in one step h_i of the piston is presented in Figure 4.

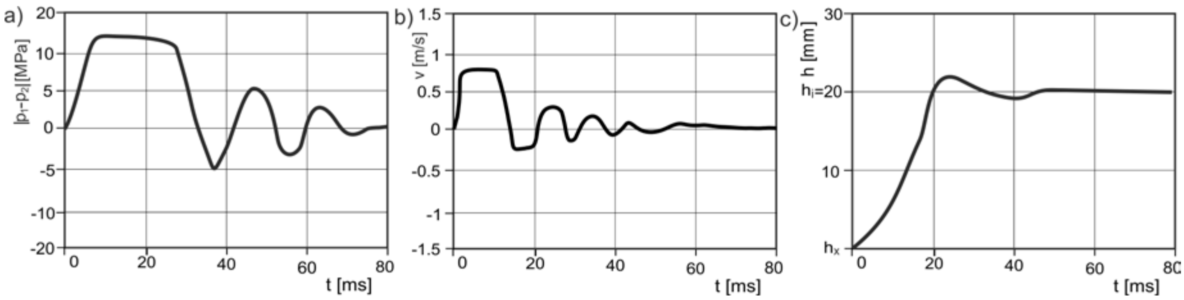

Fig. 4. Dynamic characteristics in one step positioning of the sensorless hydraulic linear stepper actuator

For the estimation of the dynamic properties of the hydraulic linear stepper actuator the following control quality factors are assumed: δ_p - overshot, t_p - setting time, T - time constant, δ_o - oscillation and $|\delta h|$ - position deviation. The following values of quality factors are obtained for a linear hydraulic stepper actuator: δ_p = 5 %, t_p = 80 ms, T = 33 ms, δ_o = 75%, $|\delta h|$ = 1.1 mm. The accuracy of the actuator piston position is within permissible 5% deviation, i.e. $|\delta h| \leq 0.05\ h_i$.

5. Conclusions

This paper presents a new solution and working principle of a sensorless position control system of hydraulic linear stepper actuator controlled by a combination of single binary on/off valves. The working principle of the hydraulic linear stepper actuator as well as the control equation for the combination of single binary on/off valves are described. The binary (2/2-way seat) valves used to control the position of actuator piston have several benefits: they are inexpensive, reliable, insensitive to contamination and have zero leak. The control of the on/off valves is simpler in relation to the servo-valve and easier with the controller. The position control of stepper actuator often requires making a step move to a new position and maintaining this position for a long time. A sensorless position system has the advantage of being controlled accurately in the open-loop position control without feedback needed to position the hydraulic linear stepper actuator. Since position feedback sensor is not required, it allows cost savings when compared to the servo-control system. The bond graphs method was used for dynamic modelling and CAMPG/MATLAB environment for digital simulation of the sensorless position control system of hydraulic linear stepper actuator. The solution of the sensorless position control system of the hydraulic linear stepper actuator will be patented. Next, the prototype model will be made and experimental tests will be carried out. The prototype of the sensorless hydraulic positioning system meets almost all design goals and shows a high potential for practical applications.

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