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Sensorless step positioning of hydraulic linear actuator

Bezczujnikowe krokowe pozycjonowanie hydraulicznego aktuatora liniowego

Abstract

The paper presents a design, working principle and simulation of a sensorless position system whose hydraulic linear stepper actuator is controlled by a combination of single binary on/off valves. For dynamic modelling and digital simulation of stepper actuator, the bond graph method was used. Preliminary simulation tests were conducted to determine the dynamic characteristics and dynamic properties of the stepper actuator.

Keywords: stepper actuator, positioning system, sensorless control

Streszczenie

W artykule przedstawiono projekt, zasadę działania i symulację bezczujnikowego układu pozycjonowana hydraulicznego liniowego aktuatora krokowego sterowanego kombinacją pojedynczych binarnych zaworów włączających/wyłączających. Do modelowania dynamicznego i symulacji cyfrowej aktuatora krokowego wykorzystano metodę grafów wiązań (bond graph). Przeprowadzono wstępne testy symulacyjne w celu określenia charakterystyk dynamicznych i właściwości dynamicznych aktuatora krokowego.

Słowa kluczowe: aktuator krokowy, system pozycjonowania, sterowanie bezczujnikowe

1. Introduction

Hydraulic positioning systems should meet such requirements as precision position and high operational reliability irrespective of the load mass and the speed of the working movement. The sensorless control system for positioning hydraulic linear actuators (cylinders) and rotary actuators (motors) is presently an alternative to traditional servo control with servo or proportional valves. In the paper [3] a new type of a linear hydraulic stepper drive for sensorless positioning tasks in hydraulics is discussed. The paper [4] presents the idea of Digital Hydraulics (DH), which consists in replacing the expensive and sensitive servo valve with a combination of simple, robust and low-cost binary on/off valves. The advantages of Digital Hydraulic Systems (DHS) are as follows: potential increase of efficiency, redundancy, robustness and higher accuracy in machine movements. Furthermore, they include lower energy usage, fewer shutdowns, less lost production and lower initial investment and spare parts carrying cost. DHS focuses on unconventional control which involves the use of binary on/off valves for direct control of the hydraulic linear stepper actuator. The paper deals with a design, working principle and simulation of the sensorless step positioning with the hydraulic linear stepper actuator controlled by a combination of binary on/off valves. The practical use of hydraulic linear stepper actuators was considered, especially for moving an object and maintaining its position automatically in machine tools during manufacturing processes (welding, drilling, riveting, punching) and for precise positioning of lasers, sensors or limit switches.

2. Design and working principle of sensorless positioning of a hydraulic linear stepper actuator

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 high 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 goes through it needs. The poppet has less distance to move to stop the 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 actuator chamber. As a result of pressure difference $\Delta p = |p_1 - p_2|$, the actuator piston moves to the place of flow through outflow slots 1 and 2. In the unsteady state the p_1 and p_2 pressures in the left and right cylinder chamber can alternately increase and decrease until a fixed position of the actuator piston is achieved. The actuator piston moves until the steady state is reached 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. Outflow slots 1 and 2 with the actuator piston create symmetrical metering edge with negative overlap, as detail A in Figure 2 shows.

Different distinctive positions of the actuator piston in relation of outflow slots 1 i 2 are schematically shown in Figure 2. For each distinguished position of the actuator piston, flow rates q_{vij} (where: i –is the number of the actuator chambers, j – is the number of the outflow slots) have been marked.

On the basis of the actuator piston position (Fig. 2), the static characteristics of cross-sectional flow area A_{ij} were determined depending on the opening x and the outflow slots 1 and 2, which are shown in Figure 3.

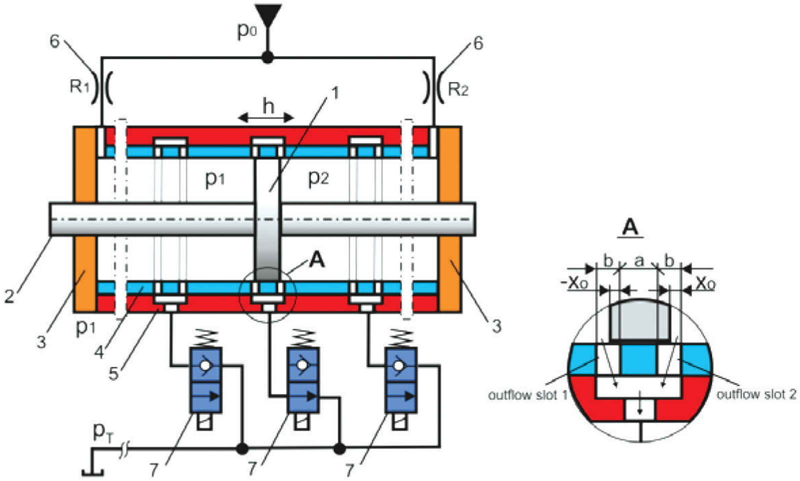

Fig. 1. Solution of sensorless positioning of hydraulic linear stepper actuator: 1 – piston, 2 – piston rod, 3 – and caps, 4 – sleeve, 5 – cylinder, 6 – throttle valves, 7 – binary on/off valves

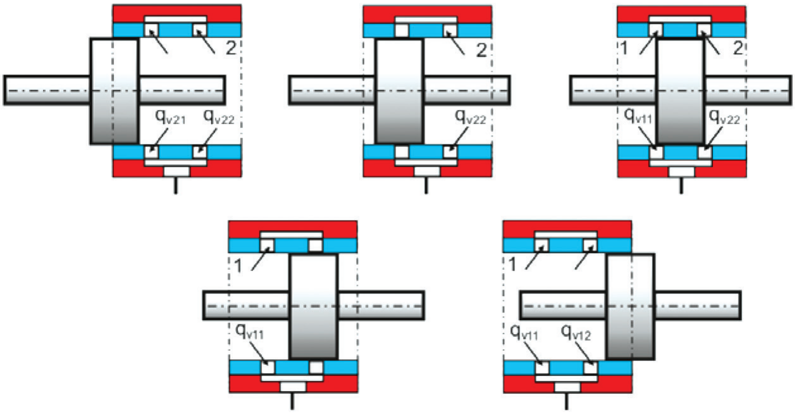

Fig. 2. Different distinctive positions of actuator piston

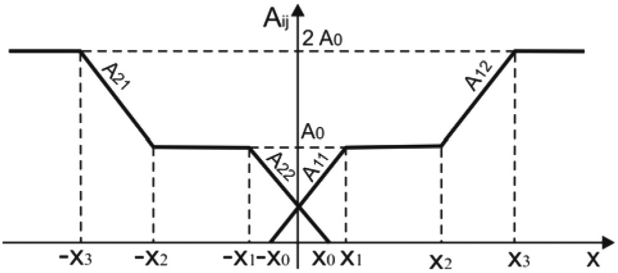

Fig. 3. Static characteristics of cross-sectional flow area A_{ij}

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

The method of Bond Graphs strictly identified with the functional structure of the hydraulic 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 ports of different bond graph nodes [5]. 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 of a hydraulic linear stepper actuator. 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 in kinetic energy storage corresponds to the mass of piston and payloads; 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. The 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. The 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 represents flow rate through the on/off valve at the actuator outlet. In the papers [2], the bond graph model of a hydraulic stepper cylinder was extended by supply conduits. A bond graph model of sensorless position control system of hydraulic linear stepper actuator is represented in Figure 4.

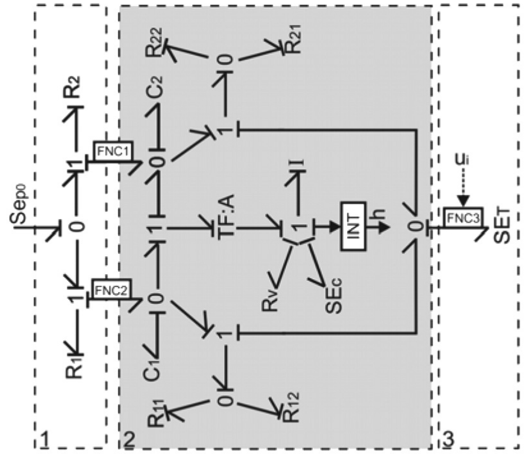

Fig. 4. Bond graph model of a sensorless position control system: 1 – throttle valves, 2 – hydraulic linear stepper actuator, 3 – on/off control valve

4. Simulation results of sensorless positioning of a hydraulic linear stepper actuator

The dynamic characteristics of a sensorless positioning system of a hydraulic linear stepper actuator was determined on the basis of the dynamic model represented by means of the bond graph method. 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 environment [1]. CAMPG takes the topological description of a physical system model described by a Bond Graph, and transforms it into a dynamic simulation model of a hydraulic linear stepper actuator in the source code form. 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 stepper actuator in one step h_i of the piston is presented in Figure 5.

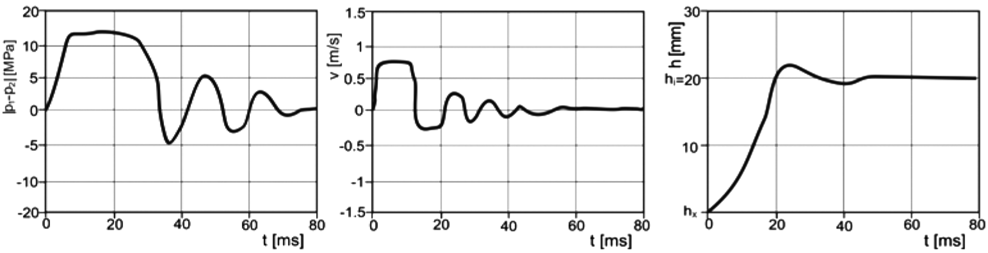

Fig. 5. Dynamic characteristics in one step positioning of the hydraulic linear stepper actuator

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: $\delta_p = 5\%$, $t_p = 80$ ms, $T = 33$ ms, $\delta_o = 75\%$, $|\delta h| = 1.1$ mm. The accuracy of the actuator piston position is within permissible 5% deviation, i.e. $|\delta h| = 0.05\ h_i$.

5. Summary

This paper presents a new solution and working principle of a sensorless positioning system of a hydraulic linear stepper actuator controlled by a combination of single binary on/off valves. The working principle of a hydraulic linear stepper actuator for the combination of single binary on/off valves is 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 a stepper actuator often requires making a step move to a new position and maintaining this position for a long time. A sensorless positioning system has the advantage of being controlled accurately in the open-loop position control without feedback needed to position a hydraulic linear stepper actuator. Since a 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 a hydraulic linear stepper actuator. The solution of the sensorless position control system of a 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 stepper actuator meets almost all design goals and shows a high potential for practical applications.

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