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Concept and modelling of the electrohydraulic valve with DC and stepper motors

Dominik Rybarczyk[1,*]

[1]Poznan University of Technology, Institute of Mechanical Technology, Poland

Abstract. The article describes concept and modelling of a new type of electrohydraulic valve controlled by the combination of a stepper motor and a DC motor. The aim of this invention is to use in the proportional valve two motors with the different properties. Both motors are responsible for the movement of a valve spool. The stepper motor and the DC motor are connected to a shaft by using a bellows coupling. Transfer from rotary to linear motion is performed by use of a bolt-nut system. According to the invention, presented here valve can be used in hydraulic drive systems with high positioning accuracy requirement. The author was granted a patent no. P.421994 on the invention described in this paper.

1 Introduction

Electrohydraulic drives allow to use one of the most important advantage of hydraulics, which is possibility to obtain large forces and moments in the relatively small dimensions and low weight of devices. For the positioning of hydraulic drives, various types of valves are used. The most commonly used electromechanical transducers are: torque motor (servo valves) or proportional electromagnets (proportional valves).

Over last 25 years, many attempts have been made to use various types of electric motors to control the movement of the spool in electrohydraulic valves – piezo elements, linear DC motors, PMSM motor, stepper motors etc. In this article, attention will be focused on the rotary stepper motors and DC motors.

Stepper motors are commonly used to drive various types of positioning devices. Due to the relatively small torque and power, they can be found in small and light machines and low-power precision devices, such as: printers, photocopiers, vehicles built-in devices, etc. The main advantage of the stepper motor is high angular positioning accuracy and an ability to work in an open control loop, which means that the angular position of the rotor (taking from the encoder) is not required. Unfortunately, due to its construction, stepper motor does not allow to perform dynamic movements. Dynamic motions are provided by DC motors. Unfortunately, accurate positioning of the DC motor requires the use of an expensive encoder and dedicated fast control system.

The author proposes combination of both types of motors in a single hydraulic valve. This solution allows to combine the advantages of both devices: high dynamics of the DC motor and high positioning accuracy of the stepper motor.

The author was granted the patent no. P.421994 on the invention described in this paper [1].

1.1 State of the art

Murrenhoff in [2] introduced an overview of trends in construction and development of electrohydraulic valves. The first chapter concerned on proportional valves with the direct drive. There are two types of electromechanical transducers used as valve elements in the valves, i.e. a stepper motor and a piezo element. In the valve with the stepping motor, a ball screw was used to transfer the drive. It moved a mechanism of independent flow control sliders. It was stated that valves using piezo materials were characterised by very good dynamic parameters compared to valves with solenoids. The experimental tests carried out on the valves showed that the drop in the transfer frequency by 3 dB occurred at 340 Hz, while the phase shift by 900 occurred at 270 Hz.

Parker proposed a proportional valve made in a technology called "Voice Coil Drive (VCD)" [3, 4]. The idea for building this type of valve comes from the design of the speakers. In contrast to a conventional proportional solenoid, in which the movable element is the core, the solenoid coil (as in a typical loudspeaker) is movable in the Parker's valve. The VCD technology has been implemented in valves from the DFplus series. These valves are characterised by limit frequencies in the 50 Hz range (without phase shift) and a small hysteresis. The improvement of the frequency response is due to the fact that a light coil is moved instead of a jumper with a much larger mass. Compared to a typical proportional electromagnet, a much wider range of displacement was achieved, in which generated force can be linear.

In his doctoral thesis [5, 6] Myszkowski describes the use of a stepper motor in a valve to obtain very low movement speed. The author

* Corresponding author: dominik.rybarczyk@put.poznan.pl

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obtained the minimum value of linear speed of a piston rod at 1 μm/s. Thanks to the use of the stepper motor, it was possible to obtain very small and precise displacements of the valve spool. However, described drive had a low maximum speed of 0.125 mm/s. In order to precisely measure the drive speed, an incremental optical position measurement system, operating at a resolution of 0.5 μm was used.

Milecki and Ortman in [7] described construction and testing of an electrohydraulic servo drive with a valve equipped with two stepping motors. The theoretical and simulation model of the valve and the entire drive was compared to the experimental research. In contrast to the solution proposed in patent [1], the valve was equipped with only one type of motor, which limited the dynamic parameters of the valve.

The article [8] focus on use of a servo motor with a cam gear for controlling a proportional valve. The motor shaft, turning special designed cam connected to the spool. Its author analysed four variants of the cam mechanism. The valve was equipped with a high torque servo motor with a maximum torque up to 15 Nm and dedicated cooling system to work with higher frequencies.

The article [9] described used of the PMSM motor (permanent magnets synchronous motor) in hydraulic valve. Its application ensured a great positioning accuracy and high dynamics of the slider movement.
The solution proposed by Parker, named Compact electro-hydraulic actuator (EHA) [10], uses a DC permanent magnet DC motor in a compact electrohydraulic drive. In contrast to the previously mentioned valves, the DC motor was used to drive the miniature pump. The actuator was equipped with a one-sided piston rod. The advantage of the solution was the ability to obtain very large forces with the need to provide a small installation space.

2 Construction of the valve

In typical proportional valve (fig. 1) the spool (1) is moved by two electromagnets (2) and two cantering springs (3). Windows have a triangular shape. Proportional valve is usually of an overlap type, and the spool is positioned on the basis of the input current.

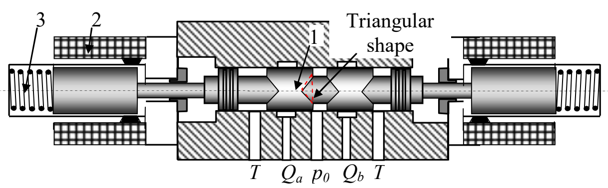

Fig. 1. Typical proportional valve with electromagnets.

The aim of the proposed invention is the use of two motors with different properties in a proportional valve (fig. 2). Both motors are responsible for the movement of the valve spool. Motors are connected to the spool via bolt-nut system. The DC motor provides high dynamics of the spool move, while the stepper motor – high accuracy. Construction of the stepper motor allows to work in relatively high temperature (about 70° C), which ensures its long life and operation in an open loop control. The DC motor with an incremental encoder (providing information about the actual position) operates in a closed control loop.

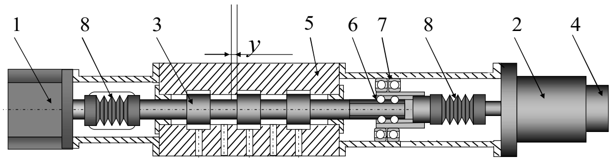

Fig. 2. Construction of the valve with motors placed on the opposite side – solution I.

The spool (3) of the hydraulic valve (solution I), moving in the sleeve, causes a change of the oil flow (fig. 2). The set point elements are the stepper motor (1) and the DC motor (2). The rotary motion is transferred to the linear motion by using a bolt-nut gear (6). The DC motor is equipped with the encoder (4). The bolt-nut gear is connected to the housing (5) via the bearing (7). Shafts of the motor are coupled by use of the bellows couplings (8). The y symbol indicates the linear displacement of the spool.

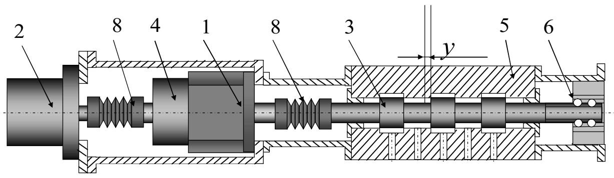

Fig. 3. Construction of the valve with motors placed on the same side – alternative solution II.

An alternative construction (solution II) is shown in fig. 3. The stepper motor shaft (1) is connected to the DC motor's shaft by the coupling bellows. The rotary motion is transferred to the linear motion by used of the gear (6). The stepper motor is equipped with an encoder placed on the back shaft (4). In case of using the DC motors with planetary gears (or another one), the proposed construction eliminates backlash problem in the gear unit. The control consists in performing the following operations: first, a dynamic, fast motion of the DC motor shaft should be made and then its power supply must be disconnected. In the next step, the stepper motor is switched on and smooth, precise motion is performed to the desired position. Due to the fact that the encoder is on the stepper motor shaft, it is possible to correct potential backlash. The propose solution does not include movable nut, which simplifies the kinematic chain. However, the valve design is less symmetrical and requires more complex control, compared to the first construction. The article focuses on the first construction.

3 Mathematical model

3.1 Hydraulic amplifier

The mathematical model of the hydraulic amplifier (fig. 4) can be described by the following formula:

$$x > 0$$

$$Q_a = K_q\sqrt{p_0 - p_a(t)} \cdot y(t) \cdot \frac{2\pi}{P} \tag{1}$$

$$Q_b = K_q\sqrt{p_b(t)} \cdot y(t) \cdot \frac{2\pi}{P} \tag{2}$$

$$x < 0$$

$$Q_a = K_q\sqrt{p_a(t)} \cdot y(t) \cdot \frac{2\pi}{P} \tag{3}$$

$$Q_b = K_q\sqrt{p_0 - p_b(t)} \cdot y(t) \cdot \frac{2\pi}{P} \tag{4}$$

where: x – displacement of the spool, Q_a – flow through the A gap, Q_b – flow through the B gap, K_q – flow factor, p_a , p_b – pressure in A and B gap, p_0 – supply pressure on valve input port, P ball screw pitch (3 mm/rev.),.

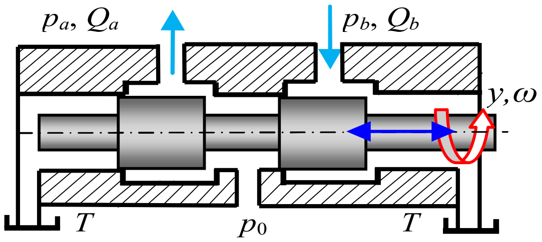

Fig. 4. Hydraulic amplifier – scheme.

A model presented here includes the square root characteristics of the flow through the gap, displacement of the spool and flow coefficient K_q which is dependent on density of the oil and the Reynolds number:

$$K_q = \mu_d \cdot \sqrt{\frac{2}{\rho}} \cdot h \tag{5}$$

where: μ_d is the discharge coefficient (0.64), ρ oil density: 900 dm^3/min, h overall width of the gap (8 mm).

3.2 Stepping motor

The mathematical model of a hybrid stepper motor can be described by use of the following formulas [11]:

$$e_A = -K_m\omega(t) \cdot \sin(N_r \cdot \theta(t)) \tag{6}$$

$$e_B = K_m\omega(t) \cdot \cos(N_r \cdot \theta(t)) \tag{7}$$

$$i_A = \int((v_A - Ri_A - e_A)/L)dt \tag{8}$$

$$i_B = \int((v_B - Ri_B - e_B)/L)dt \tag{9}$$

$$J\frac{d\omega(t)}{dt} + B\omega(t) = T_e \tag{10}$$

$$T_e = -K_m\left(i_A - \frac{e_A}{R_m}\right)\sin(N_r\theta(t)) +$$

$$+K_m\left(i_B - \frac{e_B}{R_m}\right)\cos(N_r\theta(t)) - T_d\sin(4N_r\theta(t)) \tag{11}$$

$$\frac{d\theta(t)}{dt} = \omega(t) \tag{12}$$

where: e_A and e_B – back electric and magnetic fields induced in the A and B phase windings, i_A and i_B – A and B phase winding currents (1,1 A), v_A and v_B – A and B phase winding voltages, K_m – motor torque constant, N_r – number of teeth on each of the two rotor poles, R – winding resistance (0.7 Ohm), L – winding inductance (1.4e^{-3} H) R_m – magnetising resistance, B – rotational damping, J – inertia, ω – rotor speed, Θ – rotor angle, T_e – generated torque, T_d – detent torque (0.01 Nm).

3.3 DC motor

The DC motor model can be described by the following equation:

$$m\frac{d^2\omega(t)}{dt} + D\frac{d\omega(t)}{dt} = M_{dc}(t) \tag{13}$$

$$M_{dc}(t) = K_T \cdot i(t) \tag{14}$$

$$u(t) = e(t) + R \cdot i(t) + L\frac{d\omega(t)}{dt} \tag{15}$$

$$e(t) = k_l \cdot \omega(t) \tag{16}$$

$$\frac{d\theta(t)}{dt} = \omega(t) \tag{12}$$

where m is the mass reduced in motor axis (0.1 kg), D – viscous friction coefficient (130 Ns/m), M_{dc} – motor torque, K_T – torque coefficient, L – inductance (3 mH), R – coil inductance and resistance (2 Ohm), i – current, U – supply voltage.

The rotation angle for both of motors Θ is translated to linear motion y, by use of the gear.

4 Simulation

On the basis of the equations mentioned in the previous paragraph, a simulation model was built in the Matlab Simulink software. The valve model has been divided into two parts: hydraulic amplifier and motors with a control system.

4.1 Control system

The use of two types of motors for positioning of the spool (via gear) required the use of a dedicated, specially designed control system.

The control system operated in accordance with the following algorithm (fig 5, 7, 8):

– first, the global reference signal x was set on the DC motor input. The stepper motor was stopped in this moment,
– the DC motor was positioned using the PID controller. The DC motor was equipped with a low-resolution encoder (20 pulses per revolution), so the obtained position was not accurate. At that stage, the most important thing was to make the move as fast as possible.
– when the DC motor position y_{DC} reached about 80% of the target value (this value can be changed), the stepper motor was activated. The reference position for the stepper motor x_{st} was based on the difference from the actual DC motor value and the global reference signal x. The stepper motor was positioned in open loop and micro-step mode to achieve high angular accuracy.
– the rotation of stepper and DC motors was converted into a linear movement of the valve slide by means of a gear y_{DC}. This allowed to control the flow.

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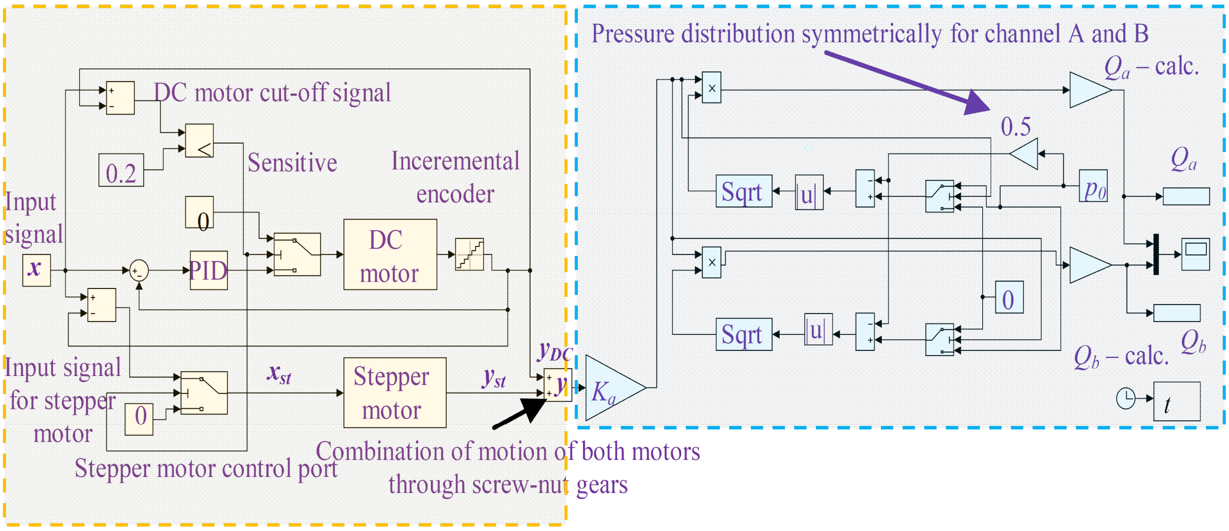

Fig. 5. Control system.

4.2 Static characteristic

The first step was to check the theoretical flow characteristics (fig. 6). In contrast to typical proportional valves with solenoids, there was no noticeable mechanical hysteresis and dead zone (proved by the author in the valve tests with the PMSM motor [8]). Maximum theoretical flow for p_0 = 30 Mpa is equal to 119 dm^3/min.

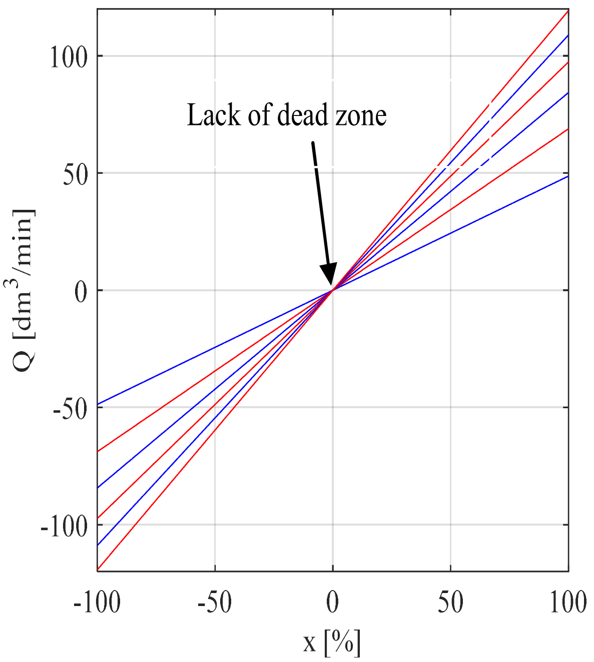

Fig. 6. Valve static characteristic.

4.3 Step response

The author verified the dynamic parameters of the valve by checking the step responses. Due to the specificity of the valve operation, values of 87% (fig. 7) and 52% (fig. 8) of the maximum opening were given for its entry.

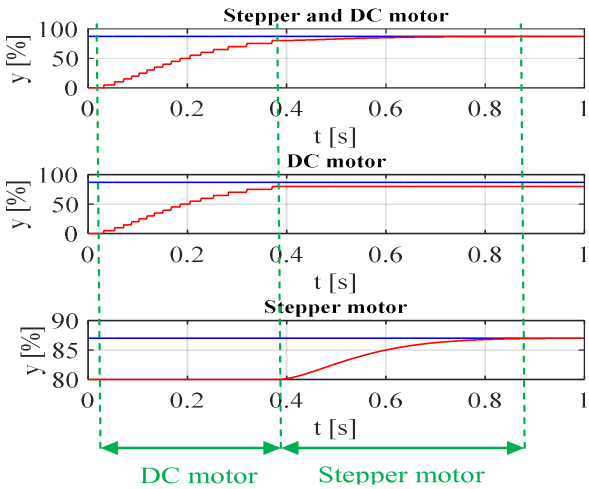

Fig. 7. Step responses for x = 87%.

Achieved set link time was equal 0.84 s (for 87% of full opening) and 0.8 s (for 52% of full opening).

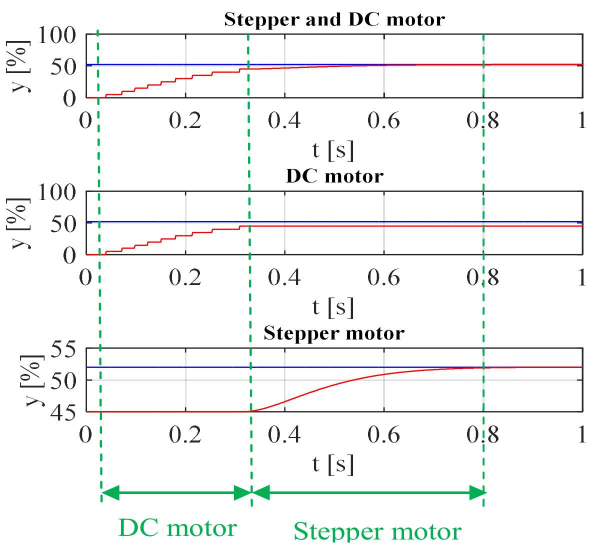

Fig. 8. Step responses for x = 52%.

The frequency response was determined based on the linearised model (fig. 9).

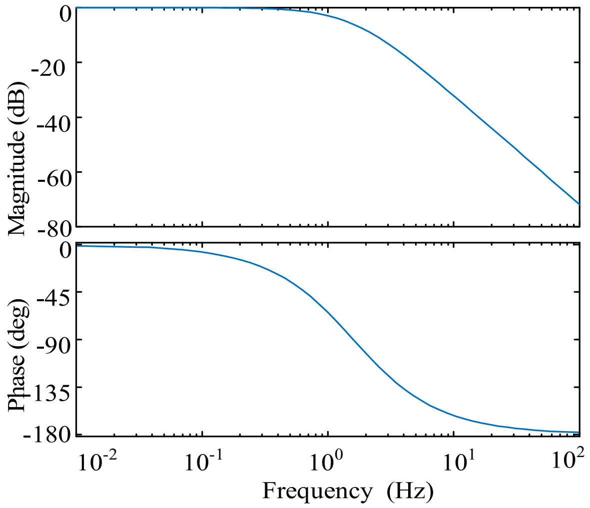

Fig. 9. Bode diagram.

5 Conclusion

The article describes an innovative, never before described, hydraulic valve, equipped with the DC motor and the stepper motor. With the literature overview, the author proved the originality of the proposed solution. The author was granted the patent no. P.421994 on the invention described in this paper.

Second part of article was focused on the simulation model. The valve required development of the dedicated control system, allowing the use of both types of motors together.

The described here electrohydraulic valve can be used for precise positioning of hydraulic drive systems and in applications where high flow rates are required. Until now, a multi-stage valve system has been typically used due to the limitations of the standard proportional valves.

Performed simulations are the starting point for construction of the valve prototype and its experimental research.

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References

1. D. Rybarczyk, A. Milecki, F. Stefanski, Patent **P.421994**, Poznan University of Technology, Poznan (2017)
2. H. Murrenhoff, Olhydraulik und Pneumatik, **46**, 4 (2003)
3. B. Bruce, *Introduction to Electro-hydraulic Proportional and Servo Valves*, Parker company training materials: http://insidepenton.com/machinedesign/BruceBesch-IntroElectrohydraulic.pdf (2018)
4. Technical documentation: *Hydraulic Proportional Valve Series DFplus,* ParkerHannifin (2007)
5. A. Myszkowski, **PhD Thesis**, Poznan University of Technology, Poznan (2003)
6. A. Milecki, A. Myszkowski, Int. J. Model. Identif. Control **7**, 3 (2009)
7. A. Milecki, J. Ortmann, ADV INTELL SYST, **440**, 73-79 (2016)
8. M. Wiegandt, *Development of a servomotor driven proportional valve*, 7 th International Fluid Conference Aachen (2010)
9. R. Rybarczyk, P. Owczarek, A. Kubacki ADV INTELL SYST, **440**, 63-71 (2016)
10. Technical documentation, *Compact electrohydraulic actuator (EHA),* http://ph.parker.com/us/en/compact-electro-hydraulic-actuator (2018)
11. Web site, *Stepper motor drive modelling*: https://www.mathworks.com (2018)