DIGITAL CONTROL OF ELECTRO-HYDRAULIC STEERING TEST BENCH

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Abstract: *The paper presents design solution and physical implementation of a system for examination of electro hydraulic steering based on OSPE 200 components. The implementation is based on synthesis of required hydraulic and structure parameters, presented in a previous paper. Now we present the interconnection of the digital control system and the closed-loop flow diagram. A formal description of embedded software is presented too, which supports operation of PI control algorithm in real-time. Experimental results for transient response prove the quality of the system.*

Keywords: digital control system, electro hydraulic steering, PI closed-loop performance

Introduction

Increasing application of mobile machines in industrial environments stimulates development of their basic power drive – hydraulic system. Important element in implementation of hydrostatic systems for mobile applications is the hydraulic steering device for direction control. It allows for control of the vehicle in several ways, depending on the generation of control signal: mechanical by steering wheel, electro-mechanical by joystick, remote based on GPS and communication networks. Therefore the application field of digital control technology expands based on its embedding capability in control loops of last generation EHSU (electro-hydraulic steering unit). For example in the last decade Danfoss PVE technology is largely used in their OSPE EHSU. These factors together with recent utilization of such mobile machines in our country form an argument to study EHSU for practical and scientific interests.

An experimental test bench system for examination of electro-hydraulic steering devices OSPE 200 is designed and implemented in the Department of Hydro-aerodynamics and Hydraulic Machines of Technical University of Sofia. The implementation is based on synthesis of required hydraulic and structure parameters of the hydraulic system elements, presented in previous our paper [1].

The purpose of this paper is to present implemented digital control system, where an industrial joystick generates the reference signal. The paper contains schematic representation of basic system components, closed-loop control system signal flow graph, and formalization of software implementation of digital PI regulator. The closed-loop performance is demonstrated by reference trajectory response of the driven servo-cylinder.

Design solution and physical implementation of EHSU test bench

For assessment of EHSU functionality, the test bench system should provide measurement capabilities of energetic (pressure and flow) and mechanical (position and velocity) physical variables. Measurement devices should be accurate enough to reliably estimate dynamic behavior of physical variables. Figure 1 shows hydraulic shematics of the test bench system, described in detail in [1].

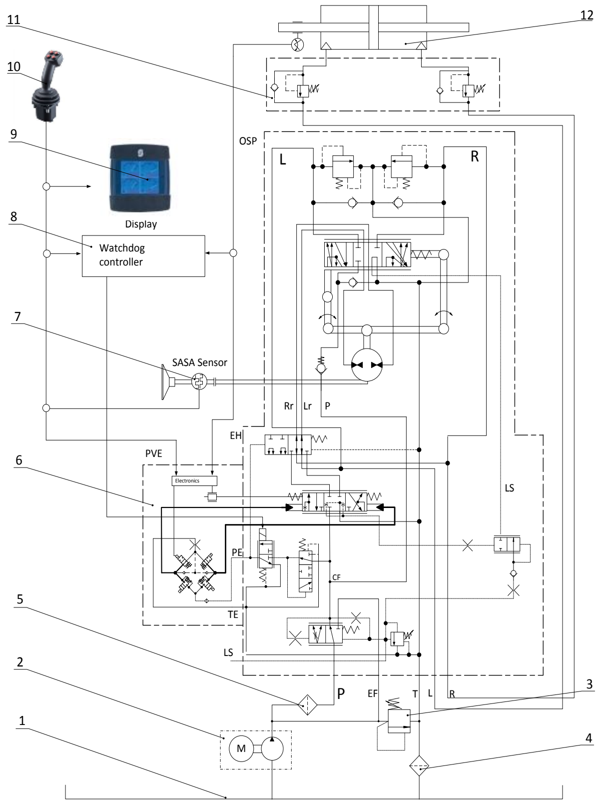

Figure 1. Hydraulic schematics of EHSU test bench with pressure loading.

Figure 2 shows 3D model and corresponding picture of the test bench system. Construction and packaging of the test bench system are in line with modern requirements for examination of electro-hydraulic steering devices with various loadings. Pressure loading system is composed of a hydraulic block with pressure reliefs valves (pos. 11, Fig. 1), which are connected to the working chambers of the servo-cylinder.

Figure 2. 3D model and implementation of test bench EHSU.

Concept of operation of test bench system of EHSU in digital control mode

Concepts of operations description of the test bench system is based on key component – OSPE 200 LSRM EHSU. Its schematic view is presented on Figure 3 [1,3].

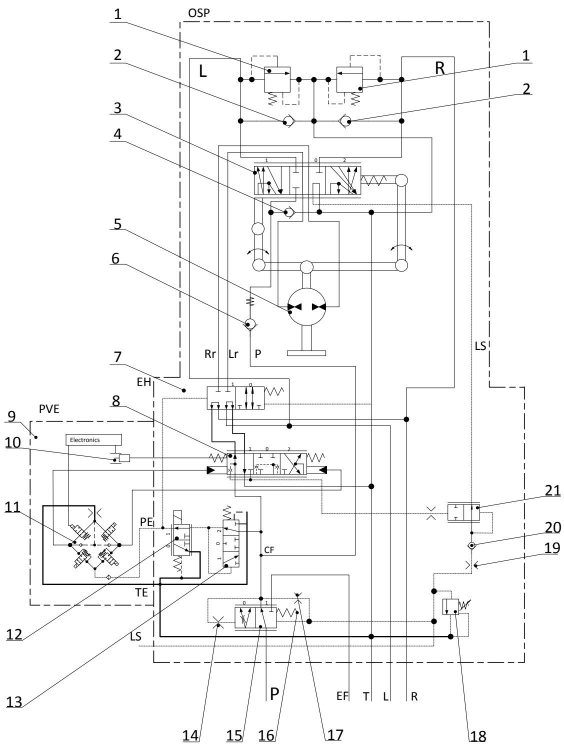

Figure 3. Hydraulic schematics of EHSU OSPE 200.

Necessary condition for the work of EHSU hence the whole test bench system in digital joystick control mode (through EH – electro-hydraulic control block for OSPE) is feeding an electrical signal on control valve for mode change (12). When the valve (12) is switched in position ‘1’ control pressure signal is required (12 bar) supported by the reduction valve (13). That signal is fed through control valve for mode selection (12) towards connected in parallel bridge 2/2 valves, which are part of digital control block (PVE, 11). Simultaneously a pressure signal is fed towards main valve, which determine the mode of control (7). It switches to position ‘1’ and connects electro-hydraulic directional valve (8) with L and R lines to corresponding chambers of the servo-cylinder. Directional valve (7) breaks the connection with lines Rr and Lr, as well as with working pair piston/ bush (3). Therefore the mechanism of steering wheel control (OSP) is isolated.

When input electrical signal from the microcontroller is received in the PWM valve controller PVE (9) (in our case the signal is for steering in right direction), parallel electromagnetic controlled 2/2 valves are activated (depending on PWM signal) and electro-hydraulic directional valve (8) switches to position ‘1’. In the LS-contour connected to directional valve (8) the pressure level is regulated by feeding the working fluid to valve (21), to be able to move the servo-cylinder in desired direction (right).

Valve (21) function is to limit the flow in LS-contour in relation to pressure drop in orifice (17) of priority valve (15). The pressure in the LS-contour acting upon priority valve (15) will correspond to required pressure in the case of control with electro hydraulic directional valve (8). Therefore the position of the priority valve (15) changes in relation to required working pressure in this mode.

Implementation of digital control system

Digital control system is developed upon microcontroller *MC012-022* and electrical joystick *JS6000* for control of electro-proportional block PVE (embedded in EHSU *OSPE 200*), which through embedded directional valve (pos.8, Fig.3) executes a control of plant’s position – servo-cylinder with equally shaped chambers. Electrical connections between components of the control system are shown in Figure 4.

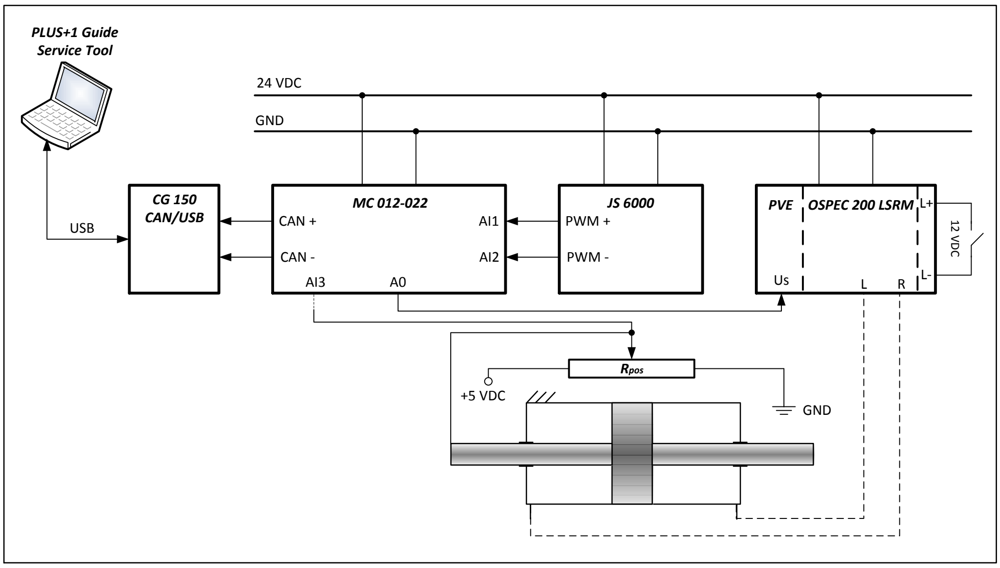

Figure 4. Conceptual representation of electrical connections of the control system

The joystick, which generates PWM signal for desired cylinder velocity, feeds correspondent analog input pins of the microcontroller. Embedded software calculates error between position feedback signal (R_{pos}) and reference signal. Analog output of the microcontroller is connected to the electro-hydraulic block with 2/2 valves (*PVE*). Its purpose is sending control voltage signal for EHSU *OSPEC 200 LSRM*. Standard CAN-network [2] is exploited for downloading of microcontroller program and data acquisition of dynamical responses. Workstation for software development accesses CAN-network through USB/CAN - device (CG150) [6].

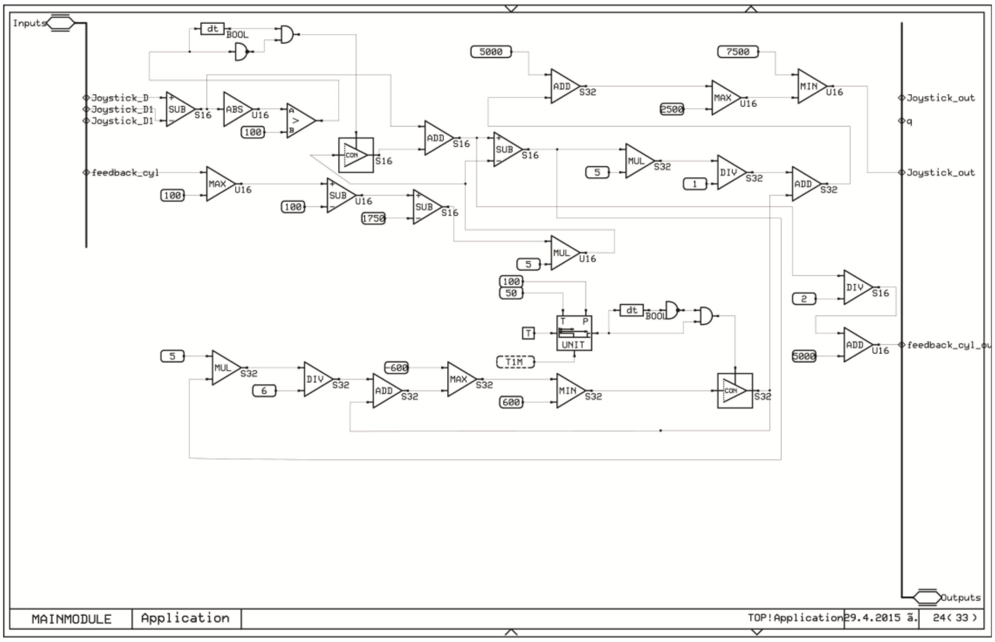

Figure 5. Software model of digital control system

We use proportion-integral control law for the position y of the piston of execution servo-cylinder. Human operator generates the reference signal x_{ref} through utilization of electronic joystick [5]. Control signal u represents voltage input for electronic block of steering device (EHSU), which drives the main cylinder. The microcontroller calculates control signal in sample times $m\,T_S$, with sample interval $T_S = 100ms$.

$$u(m\,T_S) = k_p e(m\,T_S) + k_i \sum_{j=0}^{m} e(m\,T_S) \qquad (1)$$

$$e = x_{ref} - y \qquad (2)$$

We've developed custom program (Fig.4) in software development environment (PLUS+1 Guide) [2] of microcontroller *MC012-022* [4], to compute control signal. The program is composed of functional blocks connected by data lines. After that the IDE generates executable file which is downloaded and ran on the microcontroller. Only integer data types are supported. The compiled model runs as idle thread in the microcontroller with clock period assumed $\tau < 100ns$. The sample time is $T_S = 100ms \gg \tau$, we can assume the microcontroller time to be continuous variable t.

The value of reference signal x_{ref} is defined by following expressions:

$$x_{ref} = x_J + y_R \tag{3}$$

$$y_R(t) = \begin{cases} y(t) & S_J(t-\tau) \wedge \overline{S_J(t)} = 1 \\ y_R(t-\tau) & S_J(t-\tau) \wedge \overline{S_J(t)} = 0 \end{cases} \tag{4}$$

$$S_J = \begin{cases} 1 & |x_J| > J_{LO} \\ 0 & |x_J| \le J_{LO} \end{cases}, \quad J_{LO} = 100 \tag{5}$$

The joystick signal x_J increases linearly, with constant derivative proportional to displacement of the stick. In neutral position of the stick $x_J = 0$. Current position of main cylinder y is saved at register y_R, when joystick signal disappears $x_J = 0$. Then the control algorithm stops the movement of the main cylinder at its current position. The event of disappearance of x_J is recognized through detection of falling edge of a signal S_J.

The output signal y is obtained by measuring the position of the piston of the main cylinder by means of a potentiometric transducer (*Rpos* , Figure 4). His resistance R_fb vary from 0 to 3.7 kΩ.

$$y = K_y(y_{sat} + A_y), \;\; K_y = 5, \;\; A_y = -1850 \tag{6}$$

$$y_{sat} = \begin{cases} R_{fb} & R_{fb} > R_{LO} \\ R_{LO} & R_{fb} \le R_{LO} \end{cases}, \quad R_{LO} = 100 \tag{7}$$

Output signal value is assessed by biasing and scaling of measured resistance, such that zero output to correspond to middle position of the cylinder.

Parameters of PI regulator are k_p – proportional gain and k_i – integral gain. Integer arithmetic of the microcontroller *MC012*-022 restricts these gains to be represented as rational numbers:

$$k_p = \frac{k_{p,N}}{k_{p,D}} \qquad k_i = \frac{k_{i,N}}{k_{i,D}} \tag{8}$$

Integrator element is implemented by the following two expressions.

$$x_i(t) = \begin{cases} x_i(t-\tau) + k_i e(t) & \overline{S_i(t-\tau)} \wedge S_i(t) \\ x_i(t-\tau) & \end{cases} \tag{9}$$

$$S_i(t) = \begin{cases} 0 & 0.05(2m-1) < t < 0.1m \\ 1 & 0.1(m-1) < t < 0.05(2m-1) \end{cases} \tag{10}$$

A register x_i accumulates scaled value of the error signal $k_i e$. Register value is updated in equal sample intervals T_S. This is achieved through square wave signal S_i with period 100 ms and duty cycle 50 %. A logical function $\overline{S_i(t-\tau)} \wedge S_i(t)$ detects rising edges of the impulses by generating high level signal for one interval τ. Such an interval is enough to allow accumulation of a new value.

Proportional and integral gains of the regulator are tuned so as to guarantee typical performance indices for such class systems.

Based on structure of the test bench system and technical documentation available we've suppose the following approximate model of the open-loop plant.

$$y(t) = \frac{K_C}{s} e^{-sL} F_1(u), \quad s \in C \tag{11}$$

The plant is serial interconnection of a memoryless nonlinearity F_1 and a linear dynamical transfer function $W(s)$.

$$W(s) = \frac{K_C}{s} e^{-sL} \tag{12}$$

$$F_1(u) = \begin{cases} 0 & |u| < u_0 \\ u & u_0 < |u| < u_m \\ u_m sign(u) & |u| > u_m \end{cases} \tag{13}$$

To support tuning of regulator gains and scaling factors of the digital control system elements we've developed a numerical model for simulation in MATLAB/Simulink environment – presented on Figure 6.

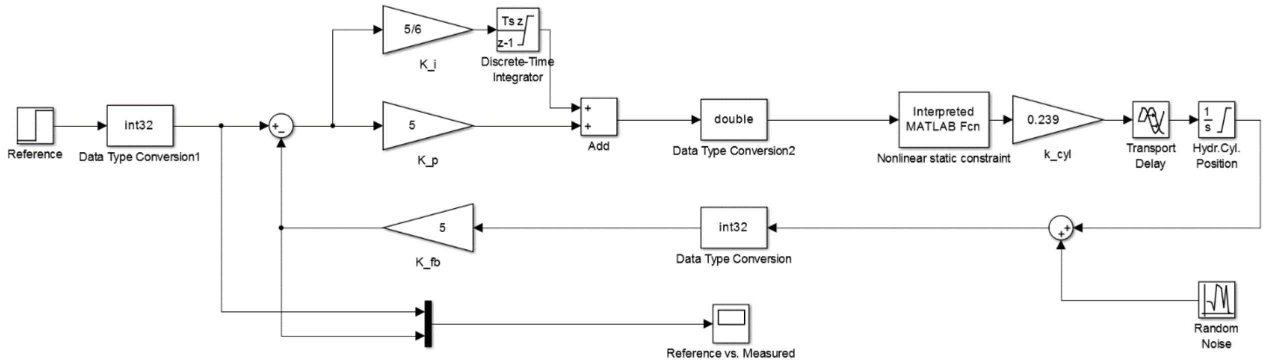

Figure 6. Simulink model of the closed-loop digital control system

Experimental results

Implemented digital control system provides capabilities for real-time data acquisition of dynamical characteristics such as: transient starting or stopping response of the cylinder; and desired trajectory tracking. The trajectory is selected by human operator through the joystick. It is possible to record simultaneously the control signal from the microcontroller to the *PVE* block, which is indicator of energy efficiency, and is often considered when tuning PI regulators. Experimental data are processed in M-script fain in MATLAB, which allows comparison of different experiments through figures or numerical measures. Usually we compare reference and output signals (R_{pos}). Figure 7 shows one experimental result of output signal dynamics.

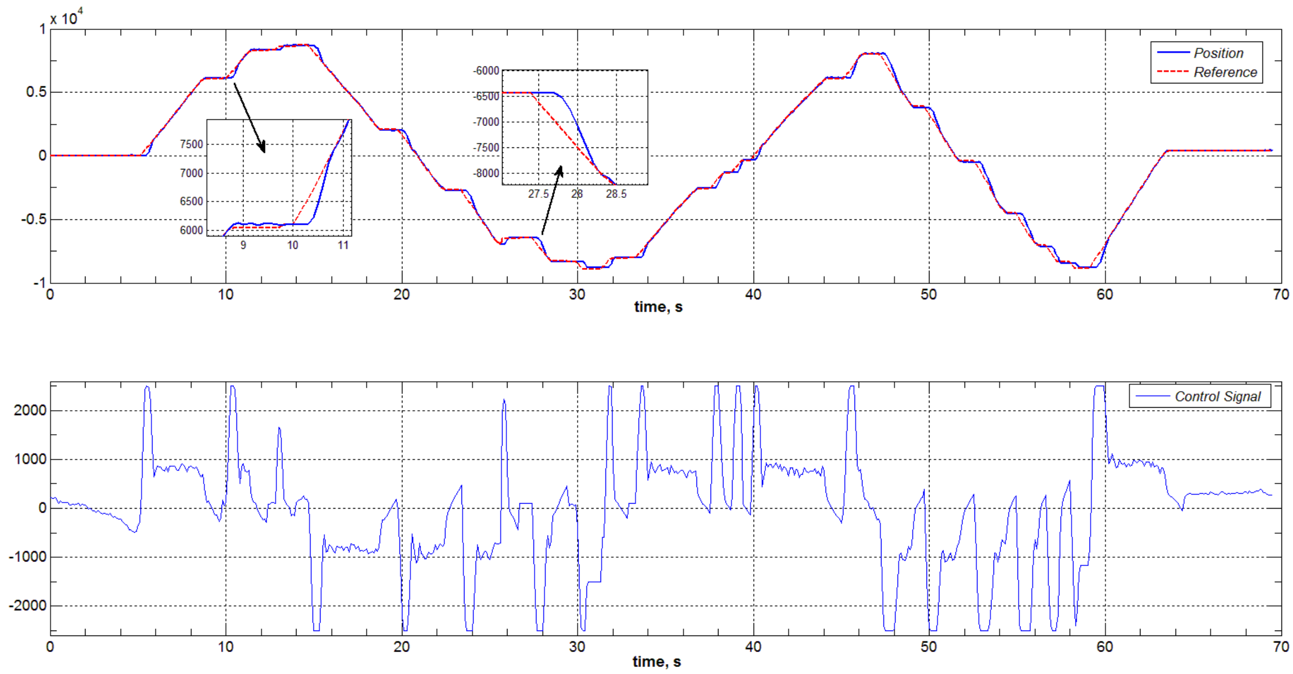

Figure 7. Experimental results – tracking of operator command

The analysis of experimental results shows:

- We observe zero error in steady state for constant and linearly increasing reference. Transient response is aperiodic without overshot.
- Settling time is smaller than 1 sec, which is comparable to human reactions.
- Control signal is close to its maximal value for the transient period, which indicates fastest output reaction.
- The performance measures are invariant in both movement directions. SNR of control signals is high which demonstrates the accuracy of the position measurement instrument. Its accuracy is distributed as quality to the whole closed-loop.
- We've estimated that position error is 0.1 mm, which is higher than human optical resolution (0.1-0.3 mm).

Conclusion

Presented implementation of digital control test bench system for EHSU and presented experimental results lead us to the following important conclusions:

1. It is developed an experimental test bench for examination of electro-hydraulic steering devices, which is capable of two modes of control:
   echanical – through steering wheel and digital - through electronic joystick.
2. Closed-loop control system shows invariant performance for large class of operator commands, which can be observed from experimental records.
3. Collected experimental data can be used for system identification to infer more accurate models which can be basis for performance improvement.

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