Test Bench for Experimental Research and Identification of Electrohydraulic Steering Units

Professor Dr.-Ing. Ilcho Angelov
Department of Hydroaerodynamics and Hydraulic Machines, Technical University of Sofia, Kliment Ohridski bld. 8, 1756 Sofia, email: ilangel@tu-sofia.bg

Dipl.-Ing. Alexander Mitov
Department of Hydroaerodynamics and Hydraulic Machines, Technical University of Sofia, Kliment Ohridski bld. 8, 1756 Sofia, email: alexander_mitov@mail.bg

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. Identification is performed based on experimentally reported the transitional process by developing mathematical models. Presents the structure and capabilities of the models for identification, as well as procedures for their validation.

KEYWORDS: Steering Units, Test Bench, Digital Control System, Identification

1. 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 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. Identification is performed based on experimentally reported the transitional process by developing mathematical models. Presents the structure and capabilities of the models for identification, as well as procedures for their validation.

2. Design solution and physical implementation of EHSU test bench

Figure 1 shows hydraulic shematics of the test bench system, described in detail in [1]. 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, Figure 1), which are connected to the working chambers of the servo-cylinder.

Figure 1: Hydraulic diagram of test bench

Figure 2: 3D-model and implementation
3. 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 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 3.

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 \( R_{\text{pos}} \) 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 is exploited for downloading of microcontroller program and data acquisition of dynamical responses.

![Figure 3: Conceptual representation of electrical connections of the control system](image)

Workstation for software development accesses CAN-network through USB/CAN - device (CG150) [2]. We use proportion-integral control law for the position \( y \) of the piston of execution servo-cylinder. Human operator generates the reference signal \( x_{\text{ref}} \) through utilization of electronic joystick [3]. 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 \( T_S = 100 ms \).

\[
u(m T_S) = k_p e(m T_S) + k_i \sum_{j=0}^{m} e(m T_S)
\]  
\[
e = x_{\text{ref}} - y
\]  

\( m, n \) - Group 10 - Mobile Hydraulics | Paper 10-7 227
We've developed custom program in software development environment (PLUS+1 Guide) 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 $\tau < 100\,\text{ns}$. The sample time is $T_s = 100\,\text{ms} \gg \tau$, we can assume the microcontroller time to be continuous variable $t$. This sample time is determined on the basis of preliminary experimental tests designed to determine the bandwidth of a system.

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

$$x_{ref} = x_j + y_R$$

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

$$S_j = \begin{cases} 
    1, & |x_j| > J_{LO} \\
    0, & |x_j| \leq J_{LO}, \quad J_{LO} = 100 
\end{cases}$$

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 ($R_{pos}$, Figure 2). His resistance $R_{fb}$ vary from 0 to $3.7\,\text{k}\Omega$.

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

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

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:
\[ k_p = \frac{k_{p,N}}{k_{p,D}} \quad k_i = \frac{k_{l,N}}{k_{l,D}} \]  

Integrator element is implemented by the following two expressions:

\[ x_i(t) = \begin{cases} 
 x_i(t - \tau) + k_i e(t) & \text{if } t - \tau < 0 \\
 x_i(t - \tau) & \text{if } t - \tau \geq 0 
\end{cases} \]

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

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 \( S_i(t - \tau) \wedge S_i(t) \) detects rising edges of the impulses by generating high level signal for one interval \( \tau \). Such an interval is enough to allow accumulation of a new value. 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 4.

**Figure 4:** Simulink model of the closed-loop digital control system

4. Experimental results

**Figure 5:** Experimental results – tracking of operator command
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. Figure 5 shows one experimental result of output signal dynamics.

4.1. Analysis of the experimental results
We observe zero error in steady state for constant and linearly increasing reference. Transient response is aperiodic without overshoot. 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).

5. Identification
Planning physical experiment to serve as a database for identification of the test system (Figure 6).

It should be noted that all three model identification not account for the possibility of pulling loading of the executive servo cylinder, since the actual steering systems, such load does not exist. In so far as possible such kind of load, the force caused by it is possible to get close to zero, but not to change the sign of its direction.

Figure 6: Experimental results for identification
• **Hammerstein-Wiener**

The first models (Figure 7) is obtained from direct observations on the behavior of the object. When submitting an input signal observed dead band of the form:

$$F_{in}(x) = \begin{cases} 
0, & |x| < 500 \\
-x, & 500 \leq |x| < 2500 \\
2500\text{sign}(x), & |x| \geq 2500
\end{cases} \quad (11)$$

With $u$ represents the control signal voltage. Its amplitude is proportional to the velocity of the piston $\dot{y}$, which is an argument for introducing an integrated unit. There has been some delay $\tau$ of the reaction, at a step change in control.

$$y(t) = F_{out} \left( K \int_0^t F_{in}(u(t-\tau)) d\tau \right) \quad (12)$$

The geometric motion of the piston is limited by the body of the cylinder, which is accounted for in the model as a nonlinear element - limitation.

$$F_{out}(x) = \begin{cases} 
x, & |x| < 9000 \\
9000\text{sign}(x), & |x| \geq 9000
\end{cases} \quad (13)$$

The numerical values of the parameters are determined by the appropriate experimental measurements.

![Figure 7: Simulink model of Hammerstein-Wiener](image)

• **Physical analogy**

The second model (Figure 8) was prepared using the information available on the constructive elements that make up the steering and PVE blocks.

![Figure 8: Simulink model of Physical analogy](image)
\[ y = F_{lim} \left( \int_0^t v_{cyl}(\tau) \, d\tau \right) \]  

(14)

Velocity \( v_{cyl} \) is proportional to the movement of \( y_{servo} \) of integrated valve:

\[ v_{cyl} = y_{servo} - k_2 \, v_{servo} \, y \]  

(15)

In addition, the compressibility of the working fluid introduced perturbation \( -k_2 \, v_{servo} \, y \) on speed, which is formed by nonlinear feedback. Our reason for this is the equation for compressibility \( \frac{\Delta V}{\Delta P} = -KV \) for executive cylinder. After separation of \( \Delta t \), to yield \( q = -KV \dot{P} \). Accepted the following linear relationships: \( q = K_q \, v_{cyl}, V = K_V \, y, P = K_P \, y_{servo} \). Therefore \( v_{cyl,q} = -k_2 \, v_{servo} \, y, k_2 = K_P K_V / K_q \). The integrated valve is presented as an integrated unit with saturation:

\[ y_{servo} = F_{lim} \left( \int_0^t v_{servo}(\tau) \, d\tau \right) \]  

(16)

His movement \( y_{servo} \) is controlled by internal feedback, closed in PVE blocks. The speed of integrated valve is formed by the managing flow electro hydraulic unit \( u_{PVE} \) and disturbance resistance forces of friction. When taking into account viscous friction \( F_v = -k_v v_{cyl} \), it will appear on factors forming of the flow rate \( q_{cyl} \), ie on \( v_{servo} \).

\[ v_{servo} = u_{PVE} - k_3 \, v_{cyl} \]  

(17)

Electro hydraulic unit has been recorded as aperiodic unit with gain, ie as a real gain element. Delays introduced \( \tau_{el} \), caused by the accumulated delays of the electrical components.

\[ \frac{d}{dt} u_{PVE} = -\frac{1}{T_s} u_{PVE} + k( u(t - \tau_{el}) - y_{servo} ) \]  

(18)

The values of the parameters of this model are determined by conducting an optimization procedure that aims to a minimum of functional values of the weighted error of the model.

\[ J = \sum_{k=0}^{100} \left( y_{exp}(k \, T_s) - y(k \, T_s) \right)^2, \quad T_s = 0.1s \]  

(19)

Experimental data are divided into two parts - for identification (first 100 points) and validation (all others).

- **Non-linear ARX model**

The third of the models used Has been nonlinear ARX model (Figure 9), in which overlooked a priori information about the structure of the system and is accountable only its input-output (functional) behavior.
The movement of the executive cylinder $y$ is represented as a nonlinear function $F_{tree}$ of four variables - two past values of movement and two past values of the control voltage.

$$y = F_{tree} \left( y(t - 0.1), y(t - 0.2), u(t - 0.1), u(t - 0.2) \right)$$

(20)

Non-linear function is formed by a plurality of linear relationships $(C_k \ddot{x} + c_k)$ with various definitional areas $M_k$.

$$F_{tree}(\ddot{x} \in M_k) = d + (L + C_k)\ddot{x} + c_k$$

(21)

$k = 1 \ldots N$

Obtained defined value range are $N = 31$ in number and form a logical structure of the binary tree. It has a top 31 each of which has two branches (without the latter). For each vertex $k$ can determine who has been left $l_k$ and who is the right $r_k$ element.

$$\forall \ k \ B_k \ddot{x} < b_k \Rightarrow \ddot{x} \in M(l_k)$$

(22)

$$\forall \ k \ B_k \ddot{x} \geq b_k \Rightarrow \ddot{x} \in M(r_k)$$

(23)

$l_k$ – determine the number of elements located in the left branch to the top $k$. $r_k$ – determine the number of elements located in the top right branch $k$. $M_k = M(k)$ is admissible subset of nonlinear function, which is responsible top $k$. Typically, the input vector belongs to several peaks, i.e. $\ddot{x} \in M_{l1}, M_{l2}, \ldots, M_{lZ}$. To determine the value $F_{tree}$ calculated confidence intervals $\Delta F_{tree}(\ddot{x} \in M_{l_k})$. The value of the function is selected based on the smallest of them. $\eta_k = \sigma_k^2$ – dispersion of the error of the linear approximation in; $M_k$. $D_k$ – correlation matrix of parameters.

$$\Delta F_{tree}(\ddot{x} \in M_k) = \sqrt{\eta_k \ddot{x}^TD_k\ddot{x} \ln N^2}$$

(24)

Non-linear function is determined on the basis of experimental data, by command of MATLAB nlarx. It uses an iterative algorithm that first peak covers all defined value
range, and each node of the tree corresponds to a separation of defined value range $M_k$ two by hyper-plane with normal vector $B_k$.

6. Validation of identification models

Figure 10: Comparison of results – Measured vs. Identification models.

**Fig. 10** show a comparison of the three models for the identification in the time domain. The calculated level of FIT of the response of the model compared to the experimental data according to the expression:

$$FIT = 100 \left(1 - \frac{\|y - y\|_2}{\|y - \hat{y}\|_2}\right), \%$$  \hspace{1cm} (25)

Figure 11: Correlation characteristics of the error of modeling
Figure 11 depicts the correlation characteristics of the modeling error \( e = y - \hat{y} \). With yellow color is marked statistical limit, below which runs the hypothesis of lack of correlation (in approximation to a normal distribution of the error). The model makes the most information about the object from the data if \( \hat{y} \) is the orthogonal projection of \( y \) onto the space of regressors (measured or transformed data), i.e. if, \( \hat{y}_k = E(y_k | u_{k-m}) \Rightarrow E(e_k \hat{y}_{k-m}) = 0 \) and \( E(e_k u_{k-m}) = 0 \). In addition, under the same conditions density distribution of the output value of the model and the object, the error has the character of white noise \( E(e_k e_{k-m}) = 0 \).

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

1. Closed-loop control system shows invariant performance for large class of operator commands, which can be observed from experimental records (positioning accuracy 0.1 mm).

2. An identification of a hydraulic drive system, consisting mainly of EHSU and equal servo cylinder by three nonlinear model. The data for the identification are obtained on the basis of an intended purpose for this experiment in the form of transient characteristics.

3. After validation of the compiled models is found that all three structures it is possible to switch to the synthesis of an optimal control device. However, nonlinear regression ARX model achieves the best proximity (82.44%) in terms of dynamics (Figure 10) and statistical characteristics (Figure 11) the error modeling.

4. The compiled models of identification comprise a relatively a low level of non-linearity, which allows to perform linearization and serve to direct the synthesis and researching of the frequency characteristics of the test system.

8. References


9. Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>( u )</td>
<td>Control signal</td>
<td></td>
</tr>
<tr>
<td>( y )</td>
<td>Output signal</td>
<td></td>
</tr>
<tr>
<td>( T_s )</td>
<td>Sample interval</td>
<td>ms</td>
</tr>
<tr>
<td>( x )</td>
<td>Reference signal</td>
<td></td>
</tr>
<tr>
<td>( \tau )</td>
<td>Sample frequency</td>
<td>ns</td>
</tr>
<tr>
<td>( R_{fb} )</td>
<td>Feedback signal (Resistance)</td>
<td>kΩ</td>
</tr>
<tr>
<td>( k_p )</td>
<td>Proportional gain</td>
<td></td>
</tr>
<tr>
<td>( k_i )</td>
<td>Integral gain</td>
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<tr>
<td>( F )</td>
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<td>( v )</td>
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<td>( e )</td>
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