DEVELOPMENT AND APPLICATION OF THE DIGITAL TWIN OF THE HYDRAULIC CONTROL VALVE

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The paper is focused on the development of the digital twin of the hydraulic control valve for continuous control of the oil flow – servovalve or control valve – and their use by the testing of the control system of the test rig for the measurement and evaluation of the characteristics of the valve. The structure of the mathematical model of the control valve enables to do the parameterisation for different types and sizes of the control valves only using the catalogue data delivered by the valve producers. In the next step the created and parameterized model is implemented into the dSpace MicroLabBox for the real time realisation of the digital twin. The MicroLabBox is equipped with the analogue inputs and outputs and allows the connection of the digital twin to the control system in the same way as the real servovalve. Finally, the characteristics of the valve are measured and evaluated using the HiL simulation of the digital twin. The digital twin of the servovalve allows the testing of the developed control system and software for the hydraulic test rig for the measurement of the valve characteristics without the need of the real valves different types.

KEYWORDS

Servovalve, valve characteristics, digital twin, real time simulation, HiL simulation

1 INTRODUCTION

Modern hydraulic drives are equipped by the closed loop control systems allowing the continuous control of the important technological variables like piston position, velocity or force acting on the piston rod. The most important component of the continuously controlled hydraulic drive is the control valve, which allows continuous flow control and can be different type. The highest quality flow control with very good accuracy and high dynamics offers the servovalve typically build as a two or three stage valve. The first stage is the pilot valve, which consists of the flapper-nozzle system driven by a torque motor. The second stage is formed by the spool with four control edges. The dynamic and accurate spool positioning is performed using the first stage. Nowadays it is possible to use also the direct operated control valves for the continuous flow control. The spool is directly driven by the linear DC motor. The advantage of the direct operated valves is lower price in comparison to the servovalve. However, the dynamic properties are slightly worse and the maximal flow rate is lower [Watton 1989, Murrenhoff 2008].

The maintenance of the hydraulic system with control valves needs appropriate service, which includes the cleaning of the valve and adjusting the mechanical and electrical properties of the control valve. The valve testing is done on the test rig and finally the static and dynamic valve characteristics are measured to document the qualitative parameters of the repaired and tuned valve. The measured static characteristics are the dependence of the flow on the control signal Q=Q(u) and the dependence of the pressures in the outlet port chambers A and B on the control signal, $p_A=p_A(u)$, resp. $p_B=p_B(u)$, from which the sum is calculated $p_A(u) + p_B(u)$. The dynamic characteristics are represented by the step responses and Bode plots. The automatic valve testing and measurement of the characteristics is done using the test rig and control system which controls the measurement procedures.

The development of the test rig and control system also includes the development of the software for automatic measurement of the valve characteristics of the valves of the different types and properties. The verification of the software needs the valve testing, however, the use of the real valves would be expensive and practically impossible.

The digital twin of the control valve was developed and the simulation hardware in the loop (HiL) was applied for the proofing of the developed software and control system for control valve characteristics measurement. To be able to tune the digital twin to control valves different types, the parameter setting of the mathematical model was reduced only to the parameters given in the catalogue information of the manufactures. Finally, the digital twin was implemented into the dSpace MicroLabBox (MLB), which allows its real time simulation with the use of its I/O ports for the connection to the test rig in the same manner as the real valve.

2 MATHEMATICAL MODEL OF THE CONTROL VALVE

Derivation of the mathematical model of the hydraulic control valve was presented for example in [Jelali 2004, Watton 1989, Murrenhoff, Vyas 2019]. The presented works try to describe the real properties of the valve as precisely as possible and are focused on different nonlinearities of the valves.

The modelling of the control valve can be split in two parts: modelling of the valve dynamics and modelling of the hydraulic flow through the variable hydraulic resistances created by the four spool control edges.

The valve dynamics is determined by the type of the used actuating system which ensures the positioning of the spool. Independently on the used principle the manufacturers present in the catalogues the achieved dynamic properties using the characteristics which are typical for the linear dynamic systems – step responses and bode plots for various valve openings, although some indications of the nonlinear behaviour are observable in the given data. The spool positioning represents the positioning of the mass, which can be described using the motion equation

$$m\ddot{x} + b\dot{x} + kx = F(u), \qquad (1)$$

or using the second order term given by the transfer function

$$G_{sv}(s) = \frac{X_{sv}(s)}{U(s)} = \frac{K_{sv}}{T_{sv}^2 s^2 + 2\xi_{sv} T_{sv} s + 1}, \qquad (2)$$

where

$$T_{sv} = \frac{1}{\omega_{sv}} = \frac{1}{2\pi f_{sv}}, \qquad (3)$$

T_{sv} is the servovalve time constant, ω_{sv} is the angular eigen frequency and f_{sv} is the eigenfrequency of the valve, ξ_{sv} is the damping coefficient of the valve, K_{sv} is the gain of the valve expressed as the ratio of the maximal spool position, resp. maximal relative spool position and maximal input signal x_{svmax}/u_{max}. The values of all introduced parameters can be obtained from the catalogue data.

The spool velocity saturation is observable from the course of the typical step responses of the valve opening shown in Fig. 1. The maximal spool velocity can be identified from the linear part of the responses.

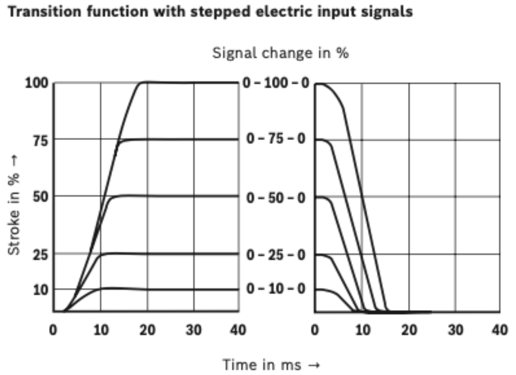

Figure 1. Typical step responses of the valve opening for different magnitude of the input step signals [Bosch Rexroth AG 2019]

The implementation of the saturation of the spool velocity into the dynamic model of the second order term allows also to achieve the behaviour of the simulation model corresponding to the bode plots depending on the magnitude of the input signals presented in the catalogues, see Fig. 2.

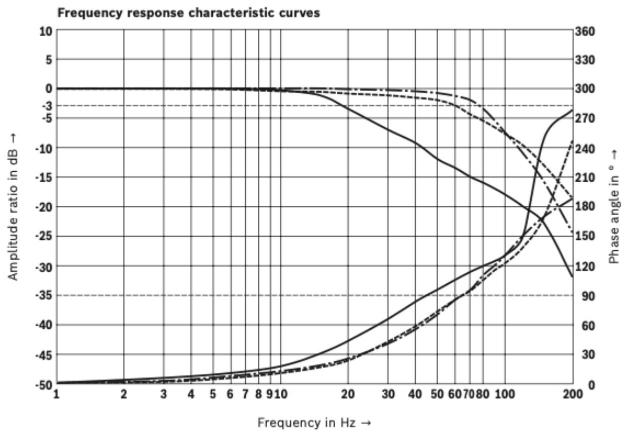

Figure 2. Typical Bode plots of the servovalve for different magnitudes of the input signals [Bosch Rexroth AG 2019]

The second part of the servovalve model is the modelling of the flow through the variable hydraulic resistances created by the four control edges *PA*, *AT*, *PB*, *BT* of the spool. The flow through each control edge depends on the valve opening x_{sv} and pressure drop across the control edge. It is expressed by the equation

$$Q_i = B \cdot abs(x_{svi} \pm x_{sv0i}) \cdot \sqrt{abs(\Delta p_i)} \cdot sgn(\Delta p_i) \qquad (4)$$
$$i = PA, AT, PB, BT,$$

where the x_{sv0} is the overlap of the spool valve, which can be positive, zero or negative and is specified for each valve. *B* is the flow gain of the control edge. The same value of *B* is used for each control edge of the symmetric valve. If the spool is modified and has different cross section areas into the outlets A and B, for example in respect to the ratio of the cross section area S_A of the piston side and S_B of the piston rod side or it has an inflected characteristics the different value of *B* is used for each control edge or the value can also depend on the spool position $B_i(x_s)$.

The created simulation model of the control valve was verified using the developed application for the simulation and evaluation of the dynamic characteristics – the step responses and the Bode plots for input signals of different magnitude. Fig. 3 shows the developed environment of the application for model testing and results of the model verifications, which confirm the non-linear behaviour of the implemented simulation model. The application has the description in Czech Language.

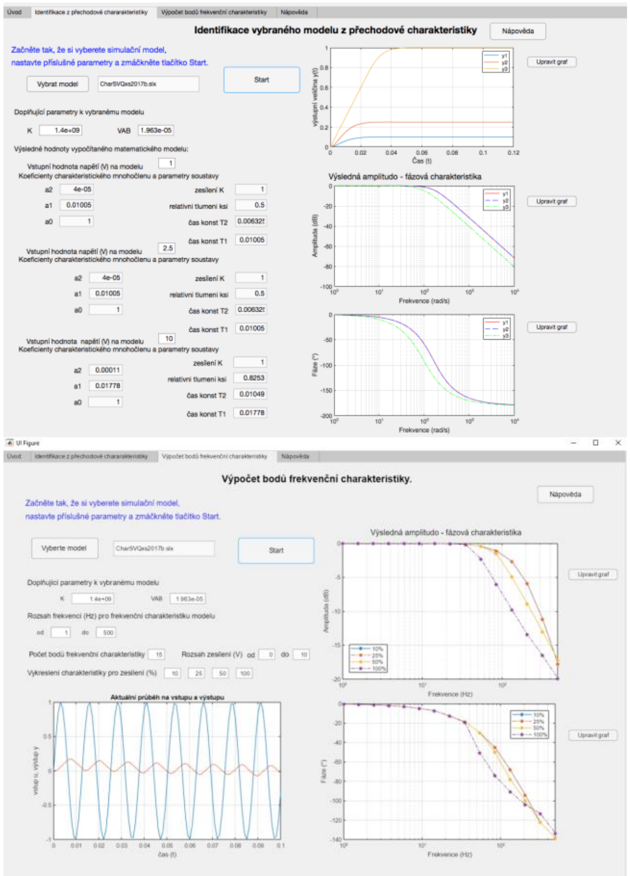

Figure 3. Application for the verification of the created simulation model of the control valve using the simulation of the dynamic characteristics for input signal different amplitude

3 STATIC CHARACTERISTIC OF THE SERVOVALVE

The valve testing on the test rig is based on the measurement of the static characteristics: valve flow - input signal function *Q=Q(u)* and pressure – input signal functions $p_A=p_A(u)$, resp. $p_B=p_B(u)$ [Jelali 2004, Murrenhoff 2008].

The valve flow characteristics is measured for constant system pressure p_0 and for smoothly changing valve opening, to get the curve showing the steady flow in dependence on the valve opening. Ideal flow – input signal characteristic is a straight line. If the valve has positive or negative overlap, saturation or hysteresis, the effects can be seen in the measured characteristic. Fig. 4 shows the simulation model for the measurement of the flow-signal function and the corresponding hydraulic circuit. The results of the evaluation of the flow characteristics are shown in Fig. 5. In the upper graph is the characteristic for negative spool overlap and in the lower graph for the positive overlap. The differences in the obtained characteristics due to the different overlaps are visible around the zero-input signal.

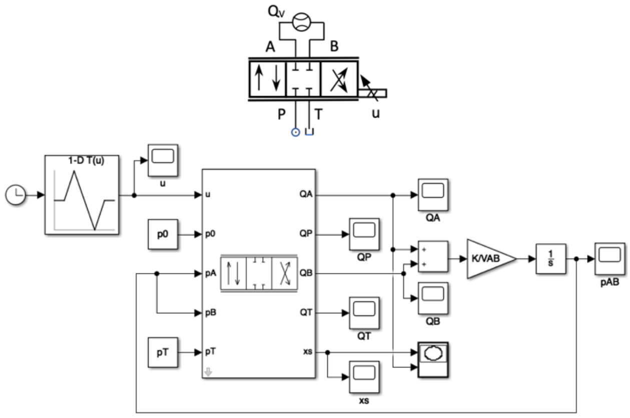

Figure 4. Simulation model for the measurement of the flow-input signal characteristics and corresponding hydraulic circuit

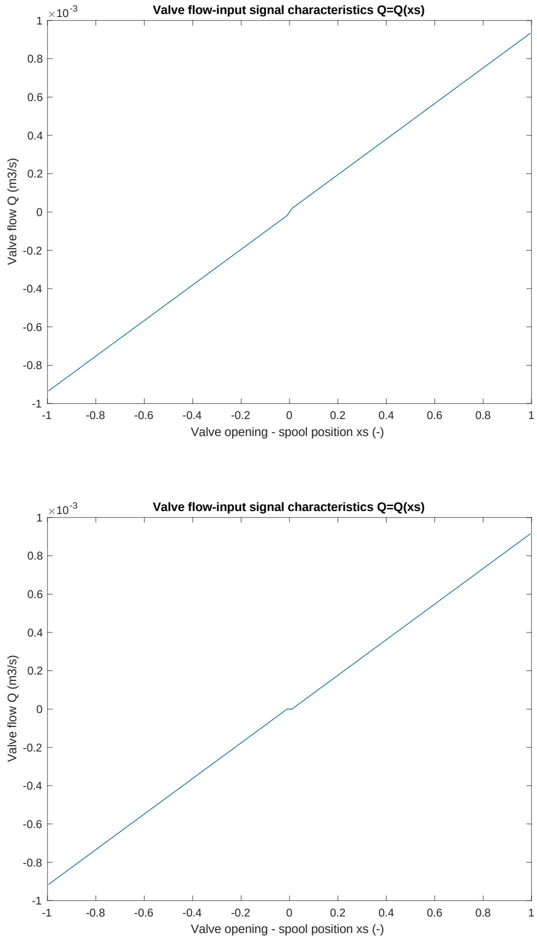

Figure 5. Simulated flow characteristics for negative (upper graph) and positive (lower graph) overlap

The pressure – input signal characteristic is typically measured on the manifold, where the outlet ports A and B of the tested valve must be closed. Fig. 6 shows the hydraulic circuit and the simulation model for the measurement of the pressure characteristics $p_A=p_A(u)$, resp. $p_B=p_B(u)$.

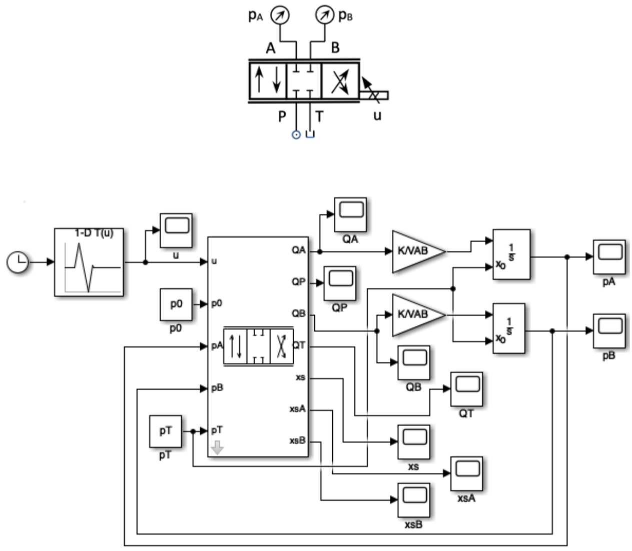

Figure 6. Simulation model for the measurement of the pressure – input signal characteristic $p_A=p_A(u)$, resp. $p_B=p_B(u)$

The typical shapes of the pressure characteristics $p_A=p_A(u)$ and $p_B=p_B(u)$ obtained using the simulation of the measurement are shown in Fig. 7. The full valve opening is for the input signal 10 V, the presented characteristic represents only 10 % of the stroke in both sides.

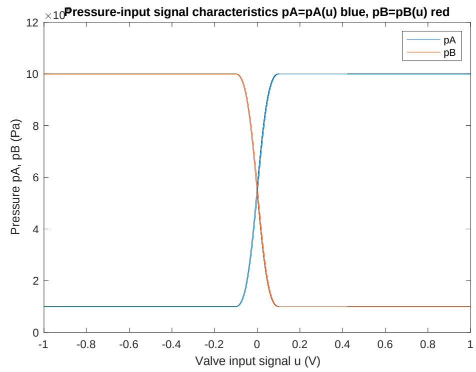

Figure 7. Simulated pressure characteristics $p_A=p_A(u)$ and $p_B=p_B(u)$

In the next step the developed simulation models of the valves and measurement processes for measurement of the characteristics of a different type were implemented into the MLB and used for the HiL simulation. The process was controlled by the control system of the test rig for valve testing.

4 SERVOVALVE HARDWARE-IN-THE-LOOP SIMULATION

To use the servovalve simulation model in the HiL scenario it must be suitably adjusted before it is uploaded to the real-time target, which is in this case MicroLabBox (MLB).

Before we generate a code from the simulation model and upload it to the MLB we must select a suitable fixed step solver and related fixed step size. The selected fixed step size and solver must ensure required accuracy and numerical stability. The limitation in this case is the computational performance of our real-time target. We can verify the fixed step solver simulation results by comparing it to the reference results, which can be obtained from the variable step simulation [MathWorks 2022].

The next step is to set the servovalve simulation model input and output interfaces. Since in our experiment, we were testing a control system for the flow characteristics measurement, we had to set the I/O interface and add blocks for the signal scaling and output saturation as can be seen in Fig. 8. There is one input block Servo Valve Input *u* and two output blocks Output Signal Q_a and Output Signal x_s. These blocks assign I/O signals to the respective I/O interfaces of the MLB that is to be connected with the I/O interface of the control system. The Input and Output scaling blocks serve for the unit conversion. The saturation blocks limit the output signal to be out of the range of allowed values. It should be noted, we must only use blocks that are compatible with the code generation on the selected real-time target.

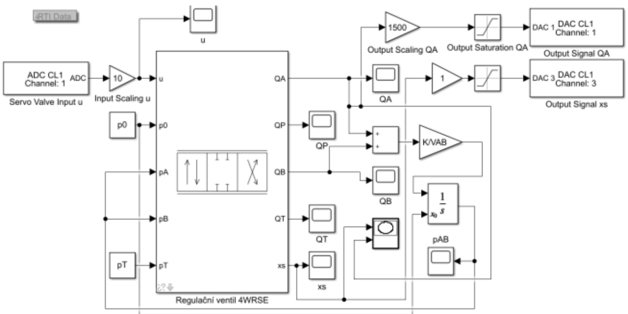

Figure 8. The servovalve flow-input signal characteristic simulation model adjusted for the HiL simulation

After the adjustment, the servovalve real-time simulation model can be generated as a code and uploaded to the real-time target MLB that is connected to the control system. The state of the simulated plant can be controlled and supervised in the ControlDesk (CD) environment (Fig. 9) that is running on the PC connected to the MLB by the ethernet. Based on the signals we want to monitor and parameters we want to set, the CD environment is prepared accordingly. The necessary files that allow setting up the CD environment are generated after the code generation and its upload to the MLB. In Fig. 9 can be seen the prepared HiL scenario environment that allows us to monitor quantities over time.

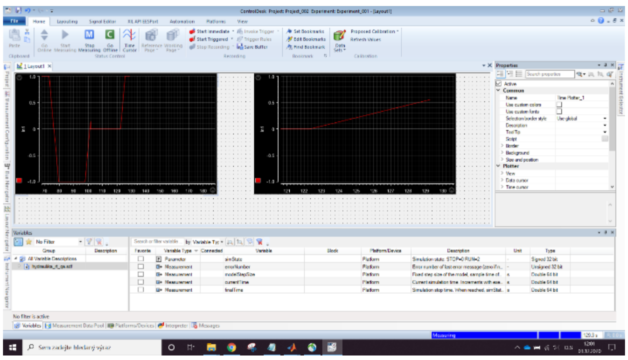

Figure 9. The HiL scenario ControlDesk environment

In Fig. 10 is a photo of the test bench control system display which shows a measured flow characteristic in the HiL scenario. This experiment allows us to test and calibrate the test bench in the laboratory conditions without the need of the real hydraulics equipment. Another advantage is that there is not a risk of damaging the real hydraulics equipment.

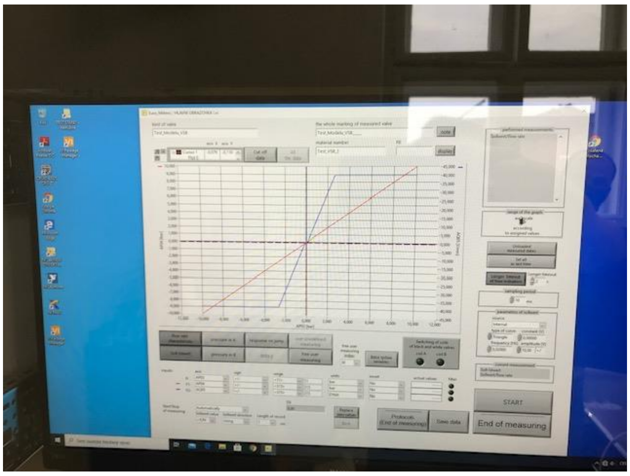

Figure 10. Measured flow characteristics of the servovalve in the HiL scenario

5 CONCLUSIONS

The paper deals with the development of the digital twins of the hydraulic flow control valve and of the measuring processes for testing the flow control valves and measurement of the typical valve characteristics. The prepared real time models of the servovalve and measurement process were used for the testing of the developed control system for the servovalve test bench. The use of the digital twins allows us to test the control system without the need of the hydraulic test rig with the manifold for placing control valves different art and also without the valves.

To be able to parameterize the created model of the control valve only from the public data, the structure of the simulation model had to be designed as simple as possible. The quality of the developed and parameterized simulation model can be tested using the prepared application. The comparison of the simulated characteristics and the characteristics stated in the catalogue can confirm the quality of the model of the control valve. The simulation models of the measurement processes for the measurement of the static characteristics – the flow-input signal and pressure-input signal characteristics – were prepared and also tested. Next the real time realization of the simulation models and HiL simulation is described. The real time simulation of the digital twin was done using the dSPACE hardware - the MicroLabBox, which allowed the connection to the control system of the test bench using the same analogue signals, that are used for the connection of the valve placed at the manifold on the real hydraulic stand and controlled using the test bench control system. The presented simulation models and HiL simulations were applied and the obtained results confirmed the functionality of the design concept.

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