Parameterization of Directional and Proportional Valves in SimHydraulics

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Abstract

Directional valves are present in most hydraulic power and control systems. The most common configurations are discrete two- or three-position valves, controlled by electromagnets, or continuous-proportional or multi-staged servo-valves, controlled by special proportional electromagnetic actuators or electrical motors. Creating an accurate model of a directional valve often requires interpreting data sheets provided by valve manufacturers. This can be a difficult task, since the data provided by different manufacturers varies. Creating a model that captures the relevant dynamics and simulates quickly can also be challenging, for these are often contradictory requirements. This paper will explain the process for creating efficient directional valve models that capture the relevant dynamics using SimHydraulics®, and show how to leverage MATLAB® and the Optimization Toolbox™ to identify parameter values that result in valve models that match the characteristics described in manufacturer's data sheets. All of the methods described in this paper are accompanied by practical examples. To download these examples, please visit http://www.mathworks.com/matlabcentral/fileexchange/27260.

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1. Directional Valve Models in SimHydraulics

The model of a directional valve can be divided into two parts: the control device and the power stage. The control device sets the position of the valve's working member (spool, cartridge, poppet, etc.) in the power stage, which controls the flow of hydraulic fluid. Two examples of directional valves represented in SimHydraulics are shown in Figures 1,a and 1,b. SimHydraulics provides engineers a very flexible tool for modeling hydraulic valves with the desired extent of idealization, from simple macro-models to detailed models capturing all essential effects.
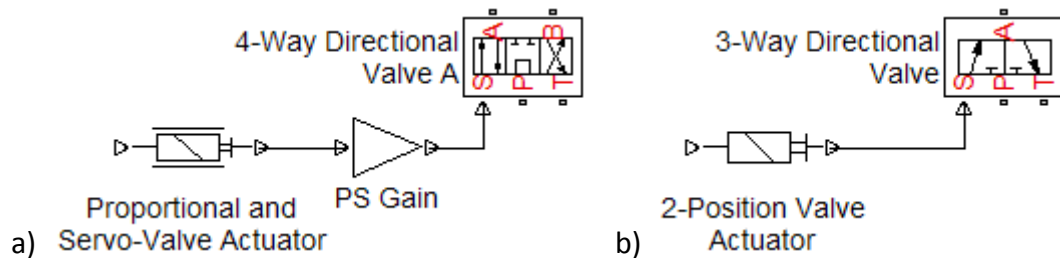

Figure 1. Directional valve structural models:
a) structural model of a proportional valve; b) structural model of the 3-way, 2-position directional valve.

When modeling a proportional or servo-valve in SimHydraulics, the Proportional and Servo-Valve Actuator block is used to represent the control device. For a conventional directional valve, the control device is modeled using the 2-Position Valve Actuator (shown in Figure 1,b) or the 3-Position Valve Actuator.

The power stage in both cases is modeled using a combination of variable orifices. Figure 2 shows a cross section and schematic for the most popular configuration of the power stage for a 4-way directional valve, and the corresponding SimHydraulics model.
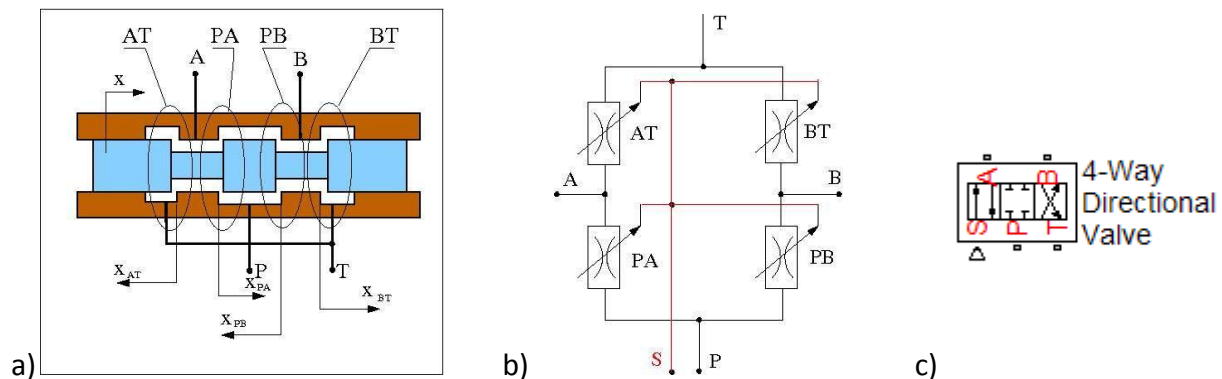

Figure 2. Structural model of the power stage of a directional valve:
a) cross section; b) hydraulic schematic; c) SimHydraulics block representing the power stage of a directional valve.
The port labels match the schematic.

The diagram in Figure 2b shows four variable orifices named for the ports they connect: variable orifice PA connects the pressure port P and actuator port A, orifice BT connects the actuator port B and return port T, etc. Port S in Figure 2b represents the mechanical translational displacement of the valve working member (spool, cartridge, poppet, etc.).

After the model has been built, the parameters have to be assigned numerical values. All SimHydraulics blocks are specified with parameters that are commonly used on data sheets. However, for a variety of reasons it can be challenging to determine all numerical values of the parameters that match the characteristics on manufacturer's data sheets. The main reason for this is the lack of standardization among valve manufacturers and on what data should be supplied on data sheets. Typically, only basic geometric dimensions and a set of output characteristics are provided. This paper describes how these characteristics can be used to determine valve model parameters and their values.

It is common practice to assign parameter values for the power stage of the valve based on the steady-state characteristics of the assembly. The dynamics of the power stage are assumed negligible because the time constants of the power stage are far smaller than that of the control unit. All dynamic effects of the valve are usually captured in the model of the control device. For these reasons, the parameterization of the power stage and the control device will be considered separately.

2. Valve Power Stage Parameterization

Every model is characterized by a set of parameters. This set is the result of the extent of idealization chosen during model development. The parameters specify the model and the process of selecting the set of parameters is referred to as specification. For SimHydraulics models of directional valve power stages, three specification options are available:

1. By specifying the valve orifice maximum area and opening. The flow rate through the orifice in turbulent regime is computed with the equation

$$q = C_d \cdot A \sqrt{\frac{2}{\rho} |p|} \cdot \text{sign}(p),$$

$$A = \frac{A_{max}}{h_{max}} h, \qquad (1)$$

$$h = x_0 +/- x$$

where

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q	Flow rate through the orifice
C_d	Flow discharge coefficient
A	Orifice area
A_{max}	Maximum orifice area
h	Orifice opening
h_{max}	Maximum orifice opening
x	Control member displacement
x_0	Initial opening
p	Pressure differential across the orifice.

The key feature of this option is the linear relationship between the orifice area and opening, which offers higher computational efficiency.

2. By providing a table-specified relationship between the orifice area and its opening. As opposed to the first option, the orifice-area relationship is assumed to be nonlinear and the value of the area is determined by interpolation. The flow rate is determined with equation (1) in which the linear area-opening relationship is replaced by a lookup table function $A=A(h)$.

3. By providing a table-specified relationship between the flow rate, orifice opening, and pressure differential. The flow rate is determined by interpolation from the two-dimensional lookup table. Normally, the necessary data is read directly from the manufacturer data sheet and no further effort is required to assign parameter values if this option is used.

The selection of a particular specification option depends on many factors, including available data, required accuracy, and simulation time constraints. The first option almost always delivers better computational efficiency, while the second and third options sometimes provide more accurate results.

2.1. Parameterization of Valves Characterized by Maximum Area and Opening (First Specification Option)

The first specification option requires three orifice parameters to be determined: orifice maximum area, orifice maximum opening, and orifice initial opening. Valve characteristics provided by the manufacturer vary by format, but the most common option is presented in Figure 3 where flow curves from the EATON/Vickers four-way proportional valve [1] are shown.
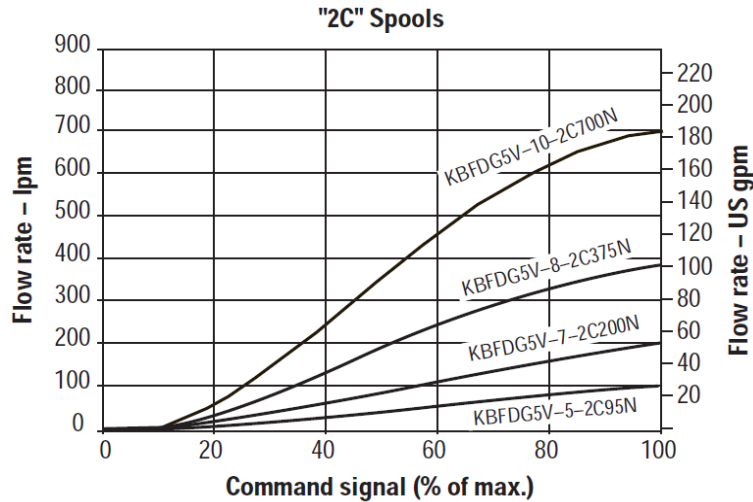
Figure 3. Example of manufacturer specification for flow rate vs. command signal.

Valve parameter values are determined using an optimization procedure in which the required characteristic for the flow rate is compared to the simulation results, and parameter values are adjusted to minimize the difference.

The first step is to build a test rig which incorporates the characteristics in the manufacturer's data sheet. As specified in catalog [1], the flow rates shown in Figure 3 are measured in the external valve loop (P-A-B-T, see Figure 2,a) with a pressure drop of 5 bar maintained on each metering path. The SimHydraulics model of the test rig for the four-way directional valve is shown in Figure 4. To maintain the pressure drop of 5 bar across every orifice, Ideal Hydraulic Pressure Source blocks are used to set the pressures at the P, A, and B ports at 10 bar, 5 bar, and 5 bar, respectively.
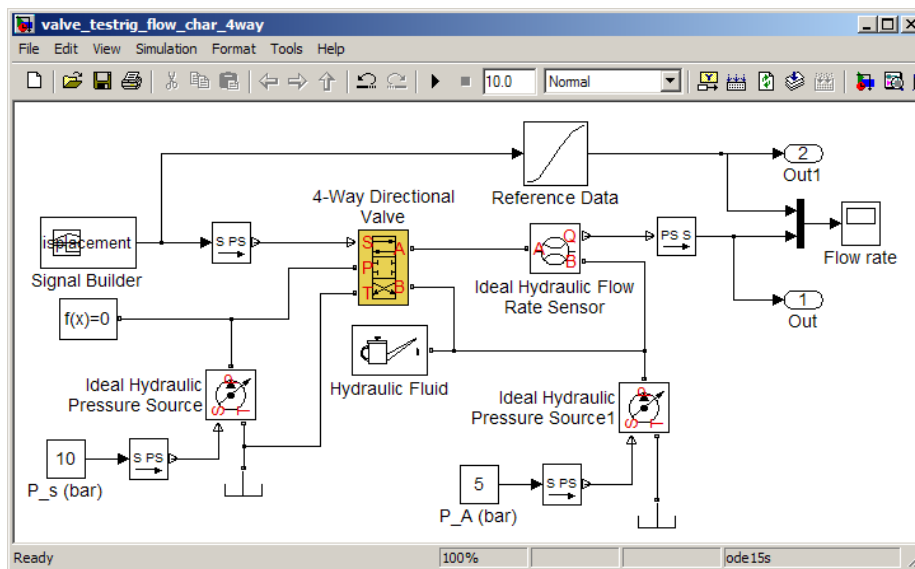

Figure 4. Model of the test rig for the determining parameter values for a 4-way directional valve

The second step is to analyze the data sheet and determine the orifice control member maximum displacement. This value is rarely included in manufacturer's data sheets. In the example considered, only the relative value of the control signal applied to the control device of the valve is provided. Both the Proportional and Servo-Valve Actuator and 2- and 3-Position Valve Actuators (see Figure 1) are ideal converters and their output is proportional to the input signal regardless of what is connected to the output. The gain block installed between the actuator and the valve (Figure 1,a) accounts for the ratio between the command signal and the valve displacement. In other words, since no dynamics are involved in the power stage model, the value of the maximum opening can be assigned any reasonable value, keeping in mind that this displacement must be provided by the control stage of the valve. For this particular example, the maximum valve displacement is set to 1 cm.

It is obvious from the characteristics in Figure 3 that all orifices are overlapped by 10% of the maximum displacement, for the flow rate becomes nonzero when the control signal reaches 10%. For this reason, the initial opening is set to -1 mm. If the initial opening is difficult to determine from the data sheet, the value must be calculated using simulation tests.

The only parameter value left to determine is the orifice maximum area. The value of this parameter is considered to be acceptable if the test rig flow characteristic matches the characteristic in the data sheet (Figure 3). The required characteristic is defined by 11 points read out from the upper curve in Figure 3 and implemented in the lookup table block Reference Results located at the top of Figure 4.

```
Input signal = 0 : 0.1 : 1;                        % [cm]

Q_r = [0 0 52 150 248 346 450 540 625 670 700];  % [l/min]
```

The control signal generated by the Signal Builder block in the model shown in Figure 4 increases linearly from 0 to 1 cm.
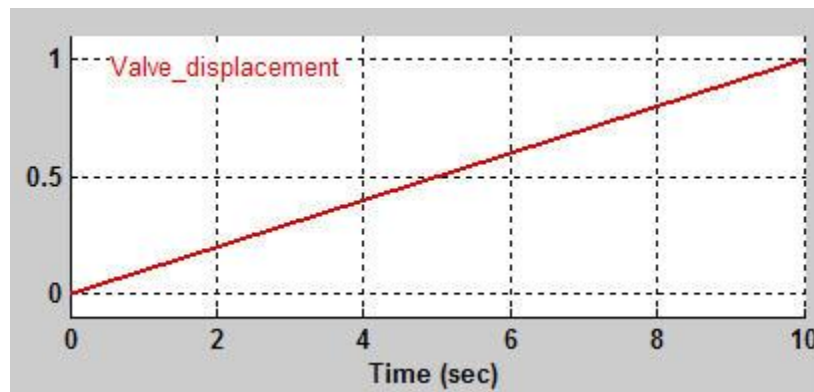

Figure 5. Control signal for valve parameterization.

To obtain 11 flow rate values for comparison with the points extracted from the data sheet, the simulation time is set to 10 s and output times are set to generate a solution at 10 intermediate points evenly spread during the simulation. The data is saved to the MATLAB workspace by the Outport block shown in Figure 4.

The objective function for the optimization is defined as the following

$$\min F(x) = \sum_{i}^{11} \alpha_i (Q_r - Q_a)^2 \tag{2}$$

where

x	Variable parameters
α_i	Weight multipliers
Q_r	Required flow rate
Q_a	Actual (measured) flow rate

The variable parameters vector in this case consists of only one parameter – the orifice maximum area (MATLAB variable *a_max*) . The problem can be solved with different MATLAB functions. The most efficient and accurate solution can be achieved with the MATLAB Optimization Toolbox™. The general MATLAB function *fminsearch* can also be used if the search surface is smooth enough.

All parameterization methods described in the paper are demonstrated by examples located in at http://www.mathworks.com/matlabcentral/fileexchange/27260. The test rig shown in Figure 4 is saved in the file *Example_1_A_max_search/valve_testrig_flow_char_4way.mdl.* The file *Example_1_A_max_search/obj_find_valve_param_a_max.m* implements the objective function (2) and the file *Example_1_A_max_search/ find_valve_param_a_max.m* is the script file that calls optimization.

In this example, the search was performed with the *fminsearch* function. The initial value was set to 4.8 cm^2 and the accuracy of the optimization was set to 1e-6. It took 22 iterations and 44 assessments of the objective function to determine that the a maximum area of 5.9648 cm^2 minimizes the difference between the required characteristic and the simulation results according to equation (2). Figure 6 shows flow characteristics before (Figure 6,a) and after (Figure 6,b) optimization.
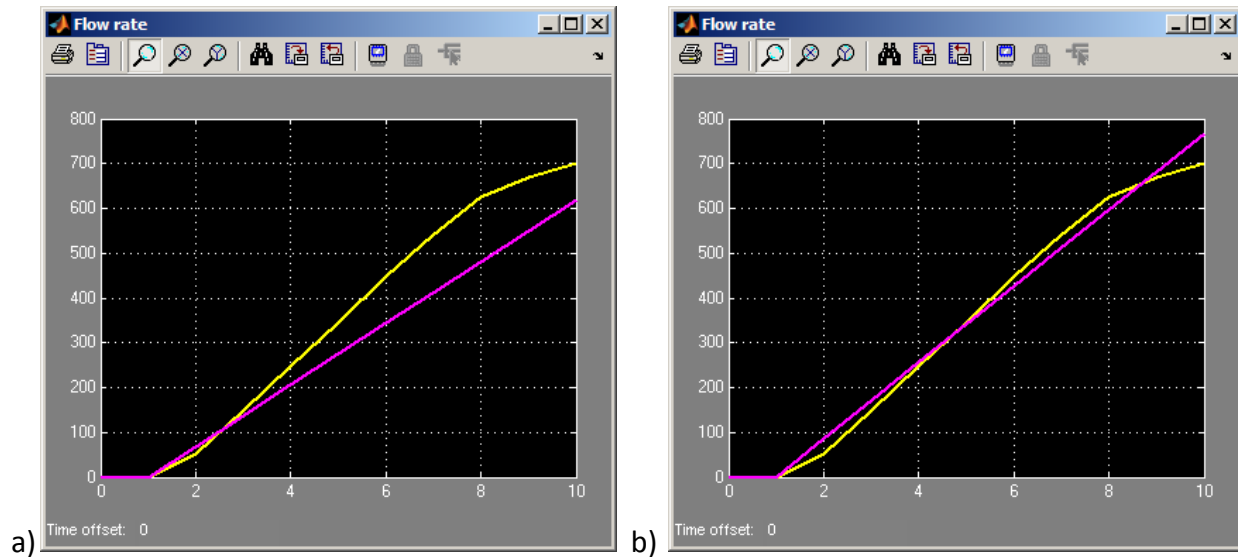
Figure 6. Flow characteristic of the valve: a) before optimization; b) after optimization (yellow line represents the required characteristic).

The discrepancy between the required characteristic and the simulation results is due to the fact that the chosen valve specification option (maximum orifice area and maximum opening with linear relationship between them) is not sufficient to reproduce the characteristics in the manufacturer's data sheet. If the control member displacement is expected to stay in the range of 0-80% of maximum opening, the results of the search can be successfully used. If a closer match is required, another specification option for the valve model must be considered.

2.2. Parameterization of Valves Characterized by Area vs. Opening Table (Second Specification Option)

With the second specification option, the orifice area is specified as a function of the control member displacement and the relationship is defined as a lookup table. Optimization is again used to tune the parameters in this table, minimizing the difference between the flow rate characteristics.

The model used during optimization remains the same as for the first option (Figure 4), with the only change to the model being the specification option for the four-way directional valve. The second specification option is used and the orifice is specified by 11 displacement-area pairs distributed evenly along the control member stroke

```
s = 0 : 0.1 : 1;           %  Valve displacement, cm
area = [0, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_10];
                           % Orifice area, cm²
```

During optimization, 10 orifice area values ($a\_1, .., a\_10$) must be determined that provide simulation results as close as possible to the required characteristic. To reduce the number of

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variable parameters, the initial opening of the valve is set to zero to allow the orifice area to account for overlap. The objective function remains the same as in equation (2).

The same model shown in Figure 4 is used for this optimization and is saved in the file *Example_1_A_max_search/valve_testrig_flow_char_4way.mdl.* The file *Example_2_Table_Area_vs_Disp /obj_find_valve_param_table_artea_vs_disp_4way.m* implements the objective function and the file *Example_2_Table_Area_vs_Disp/ find_valve_param_table_artea_vs_disp_4way.m* is the script file that calls optimization.

The initial values for the area of the orifices were set to

```
x0 = [0 0.5 1 2 3 4 5 6 7 8 9];              % [cm^2]
```

and the accuracy of optimization was set to 1e-3.

With the MATLAB function *fminsearch* it took 879 iterations and 1249 objective function assessments to find the solution. The optimization runs significantly faster using the *fminunc* function from the Optimization Toolbox, which solved the same problem in 8 steps and 108 function assessments. The parameter values resulting from the optimization are

```
area = [0 0 0.3634 1.0488 1.7333 2.4178 3.1446 ...
        3.7738 4.3677 4.6823  4.8919];              % cm^2
```

The second specification option achieves a considerably better fit with the required characteristic as shown in Figure 7.
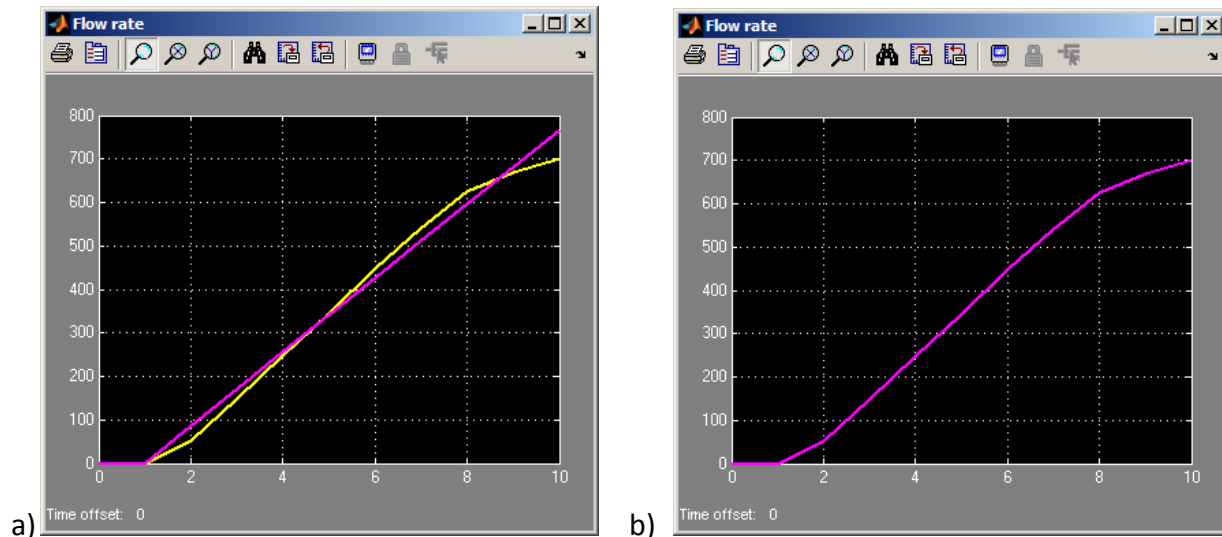

Figure 7. Parameterization results: a) with the first method of specification; b) with the second method of specification (yellow line represents the required characteristic).

The use of the second specification option requires more computation, but in exchange it results in a closer fit. The choice of specification option can be made based on the form of the required characteristics. For example, consider the flow characteristic of the ATOS Proportional Throttle Cartridge [2] shown in Figure 8 which is essentially a 3-way directional valve.
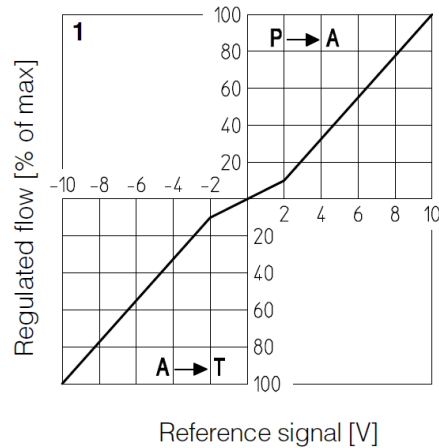

Figure 8. Flow characteristic of a 3-way directional valve (ATOS Proportional Throttle Cartridge).

The flow characteristic is clearly nonlinear. Therefore, the first specification option based on the linear opening-area relationship won't produce a good fit over the full range of the control signal. The characteristic is symmetrical which means that only the P→A branch of the power stage must be considered. The characteristic shown in Figure 8 was determined with a 10 bar pressure drop across the valve and had a maximum flow rate of 1750 l/min.

The SimHydraulics model of the test rig for flow rate measurement is shown in Figure 9 and saved in the file *Example_3_3_way/valve_testrig_flow_char_3way.mdl.*
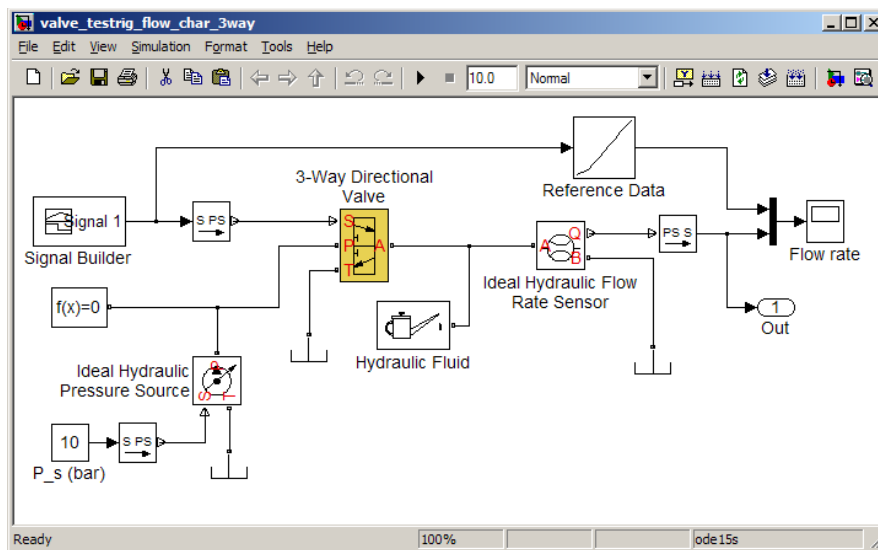

Figure 9. Model of the test rig for determining parameter values of a 3-way directional valve.

Similar to the previous example shown in Figure 4, a Simulink Lookup Table block labeled Reference Data produces the required characteristic shown in Figure 8 with 11 points evenly distributed along the valve stroke.

The objective function is the same as used in equation (2). It has 10 variable parameters which are the area values $a_1, ..., a_{10}$. The objective function is implemented in the file *Example_3_3_way/obj_find_valve_param_table_3way.m* and the file *Example_3_3_way/ find_valve_param_table_3way.m* is the script file that runs the optimization.

The initial values for the area of the orifices were set to

```
x0 = [0.4 0.8 1.5 2.5 3.2 4.5 6 7.5 9 10];          % [cm^2]
```

With the MATLAB function *fminsearch* it took 1039 iterations and 1495 objective function assessments to find the solution. The optimization runs significantly faster using the *fminunc* function from the Optimization Toolbox. The same problem was solved in 11 steps and 132 function assessments. Figure 10 shows the simulation results before and after optimization.
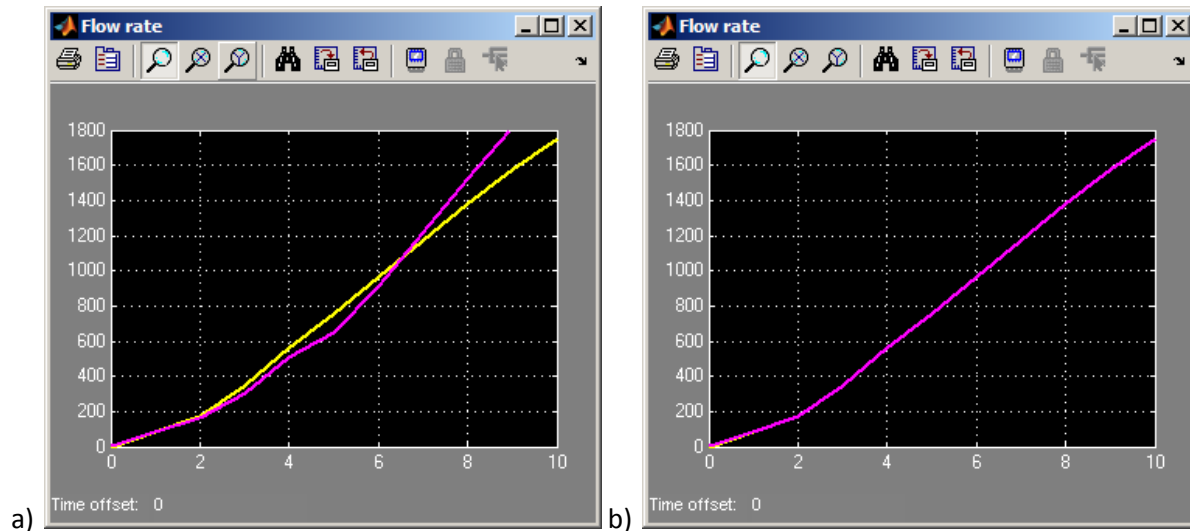

Figure 10. Flow characteristic of 3-way valve: a) before optimization; b) after optimization
(yellow line represents the required characteristic)

2.3.   Using Experimental Data for Valve Parameterization

With the second valve specification option, the values of the orifice area at specified openings can be computed analytically provided enough experimental measurement data is available. To parameterize the orifice, the following data must be available [3]:

1.   Relationship between the flow rate in the valve external loop (P-A-B-T, see Figure 4) and valve displacement at no load over a range of control signal levels

$$q_{0i} = f(x_i, p_S, p_R),$$

(3)

where

q_0	Flow rate in the external loop
x	Control signal (or valve displacement)
p_S	Supply pressure (constant)
p_R	Return port pressure (constant)
i	Measurement number, $i = 1, ..., N$
N	Number of measurements.

2. Pressures at actuator ports A and B and leakage flow through the return line with the external loop blocked measured at the same control signal levels

$$\begin{cases} p_{Ai} = f(x_i, p_S, p_R), \\ p_{Bi} = f(x_i, p_S, p_R) \\ q_{leaki} = f(x_i, p_S, p_R) \end{cases}$$

(4)

where

q_{leak}	Leakage flow through the return line

The example of the experimental data set for a symmetrical 4-way valve (see diagram in Figure 2) is saved in the file *Example_4_Experimental_Data/valve_data_file.m.* A portion of the data is shown below.

Measurement	x, volt	q_0, cm3/s	p_A, bar	p_B, bar	q_{leak}, cm3/s
1	-10	-3.2313e3	10	274.55	3.11
2	-7.85	-2.6379e3	10	274.99	3.72
3	-5.71	-2.057e3	10	274.99	4.33
. . . .					
29	5.71	2.0511e3	274.99	10	4.32
30	7.85	2.6411e3	274.99	10	3.718
31	10	3.2316e3	275	10	3.106

The measurements were performed at 31 valve positions in the control signal range from -10V to 10V. The supply pressure was 275 bar, pressure at the return port was 10 bar.

For every measurement, a system of four equations can be compiled as shown in equations (5). The equations reflect the flow continuity principle and relationship between the flow rate, pressure, and orifice area expressed with equation (1)

$$\begin{cases} C_D A_{PAi}\sqrt{\dfrac{2}{\rho}(p_S - p_0)} - C_D A_{ATi}\sqrt{\dfrac{2}{\rho}(p_0 - p_R)} = q_{0i} \\[2ex] -C_D A_{PBi}\sqrt{\dfrac{2}{\rho}(p_S - p_0)} + C_D A_{BTi}\sqrt{\dfrac{2}{\rho}(p_0 - p_R)} = q_{0i} \\[2ex] C_D A_{PAi}\sqrt{\dfrac{2}{\rho}(p_S - p_A)} + C_D A_{PBi}\sqrt{\dfrac{2}{\rho}(p_S - p_B)} = q_{leaki} \\[2ex] C_D A_{ATi}\sqrt{\dfrac{2}{\rho}(p_A - p_R)} + C_D A_{BTi}\sqrt{\dfrac{2}{\rho}(p_B - p_R)} = q_{leaki} \end{cases} \qquad (5)$$

where

A_{PA}	Orifice area in the PA path (see Figure 2)
A_{PB}	Orifice area in the PB path
A_{AT}	Orifice area in the AT path
A_{BT}	Orifice area in the BT path
P_0	Pressure in the external loop of the valve at no load. For symmetrical valve, this pressure is constant and is equal to $(p_S + p_R)/2 = 142.5$ bar.

Equations (5) can be solved for the unknown orifice areas (for clarity reasons, index i is omitted), resulting in equations (6).

$$\begin{vmatrix} -C_D\sqrt{\dfrac{2}{\rho}(p_S - p_0)} & C_D\sqrt{\dfrac{2}{\rho}(p_S - p_0)} & & \\[2ex] & & -C_D\sqrt{\dfrac{2}{\rho}(p_S - p_0)} & C_D\sqrt{\dfrac{2}{\rho}(p_S - p_B)} \\[2ex] & C_D\sqrt{\dfrac{2}{\rho}(p_S - p_A)} & C_D\sqrt{\dfrac{2}{\rho}(p_S - p_B)} & \\[2ex] C_D\sqrt{\dfrac{2}{\rho}(p_A - p_R)} & & & C_D\sqrt{\dfrac{2}{\rho}(p_B - p_R)} \end{vmatrix} \times \begin{bmatrix} A_{AT} \\ A_{PA} \\ A_{PB} \\ A_{BT} \end{bmatrix} = \begin{bmatrix} q_0 \\ q_0 \\ q_{leak} \\ q_{leak} \end{bmatrix} \qquad (6)$$

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By solving the equations in (6) for each measurement, the orifice area at each value of the control signal (control member displacement) can be obtained.

The function in the file *Example_4_Experimental_Data/dir_valve_area_characterization.m* demonstrates the way the matrix is compiled and solved. To calculate the results in MATLAB, run file *Example_4_Experimental_Data/valve_data_file.m* first to load the valve data in the workspace. Data is saved in the structure named *valve_data*.

The output of the function is matrix *area* which contains area values for each level of the applied control signal for all four orifices. For symmetrical valves, orifice values are very similar, making it possible to use the average area value for all orifices. The average area values are located in the fifth row of matrix *area*. Please note that parameter "Leakage area" of the valve block must be set to zero since leakage flow was already taken into account in equations (5).

Figure 11,a shows the relationship between the area and the control signal obtained from the calculation. Figure 11,b shows a portion of the same plot in the area of zero control signal.
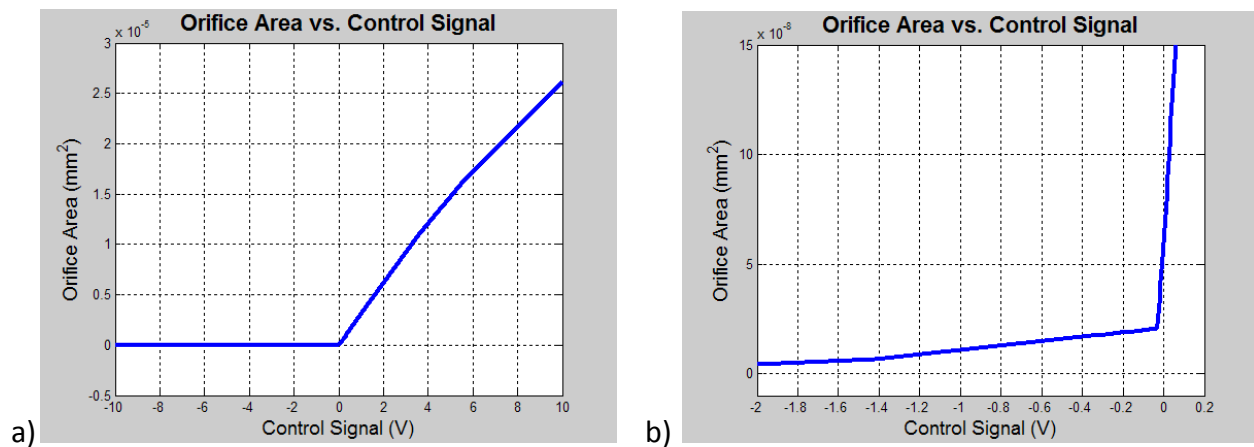

a)
b)

Figure 11. Orifice area vs. control signal calculated from experimental data.

To test the results of this process, the values were entered into a SimHydraulics 4-Way Directional Valve in the model shown below in Figure 12 and saved in the file *Example_4_Experimental_Data/valve_testrig_exp_data_4way.mdl*.
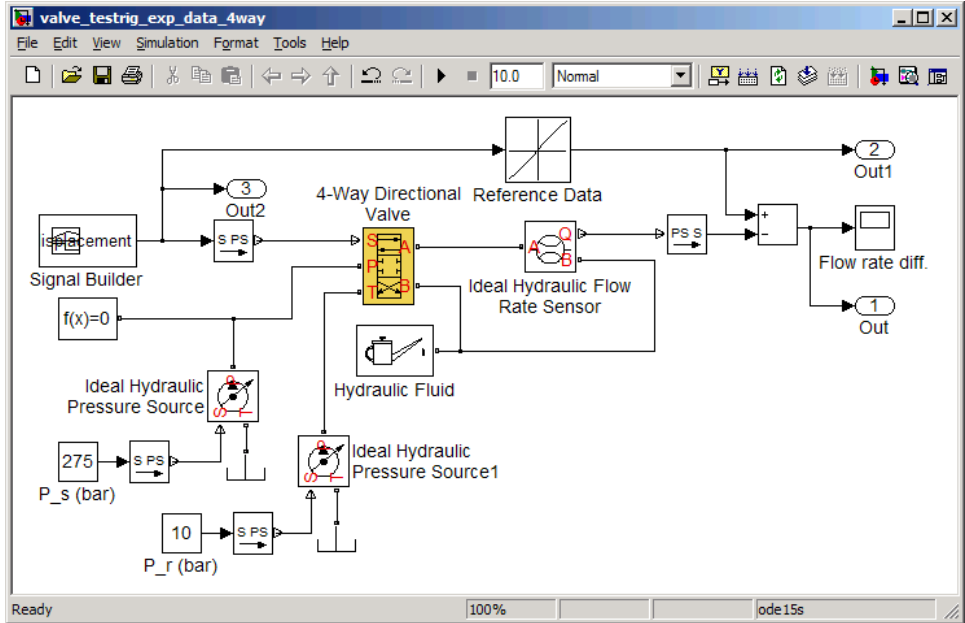
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Figure 12. Model of test rig developed to test accuracy of analytical calculations.

The test rig was configured to compare the experimental data for the flow rate (specified in the Reference Data block) and the flow rate characteristic obtained from the simulation. The relative error in percentage is shown in Figure 13. The largest error is less than 1% which can be considered as a good fit.
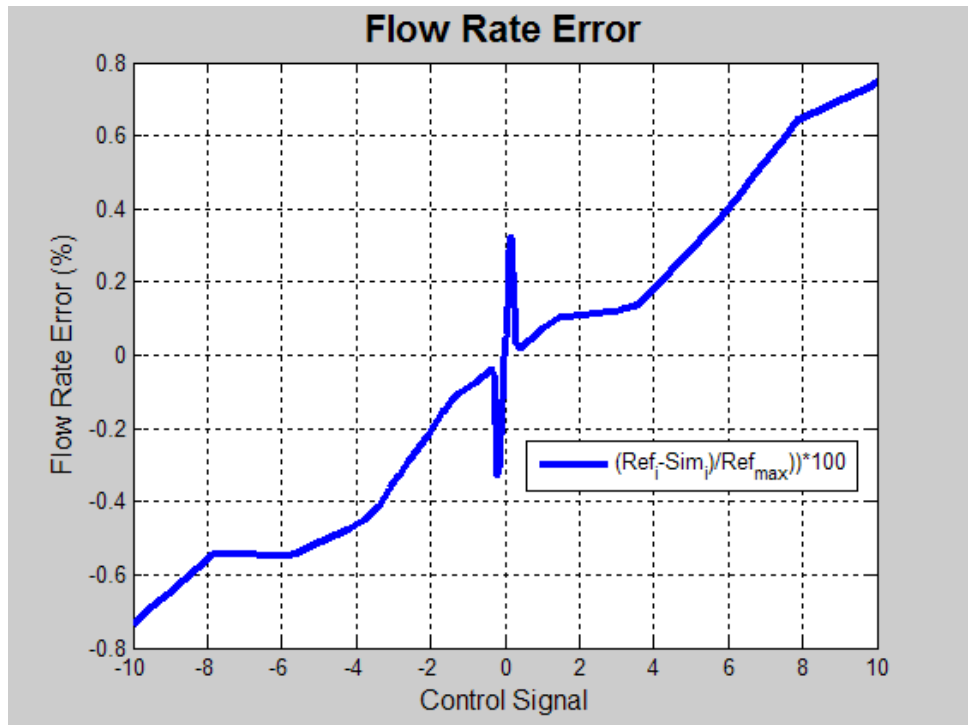

Figure 13. The relative error between the experimental data and simulated flow rate characteristics.

3. Parameterization of the Valve Control Stage

In SimHydraulics, the control stage of the valve model captures the dynamic effects of the valve. When modeling conventional, discrete valves in SimHydraulics, the control stage is modeled using either the 2-Position Valve Actuator or the 3-Position Valve Actuator. For proportional or servo-valves, the Proportional and Servo-Valve Actuator block in SimHydraulics should be used (see Figure 1). The 2- or 3-Position Valve Actuator is specified by only two parameters: push-pin stroke and response time. These values are normally provided in catalogs or data sheets, making the parameterization of discrete valves comparatively easy. Parameterization of proportional and servo-valves can require considerably more effort. For this reason, this section is mainly devoted to servo- and proportional valve actuators.

3.1. Simulink-Based Actuator Model

SimHydraulics models can seamlessly interact with Simulink models, making it possible to use Simulink to build a model of a valve control device. The model can be of any extent of idealization and any complexity. This feature is especially useful if a simple and robust model of an actuator is required for applications in which simulation speed is a limiting factor (real-time simulation, hardware-in-the-loop (HIL), etc). A more complex model can be used to tune this simpler, faster model.

A simple model of a valve actuator built entirely of Simulink blocks is shown in Figure 14. It consists of the Transport Delay block, first-order lag implemented using the Transfer Fcn block, and the Saturation block. This model can be used for both discrete and continuous actuators. This model is saved in the file *Example_5_Simulink_Actuator/ simple_valve_driver_testing.mdl*.
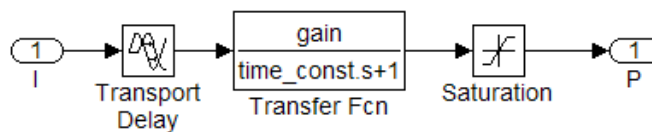

Figure 14. Simulink-based model of a valve actuator.

In *simple_valve_driver_testrig.mdl* (shown in Figure 15) the model of the Simulink-based actuator named Simple Driver is tuned to match the characteristic of the SimHydraulics 2-Position Valve Actuator.
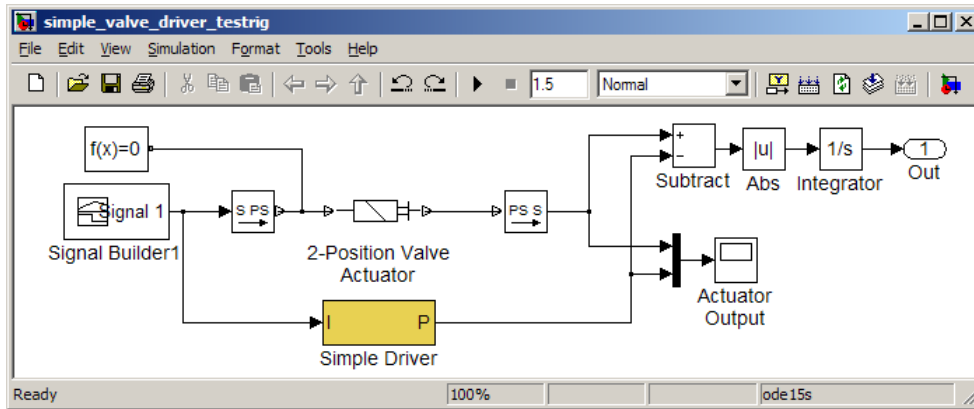
Figure 15. Test rig for tuning of the Simulink-based actuator.

Both drivers are excited by the same input signal. Their outputs are compared by the integrating the absolute value of the difference in their outputs. This is computed in the model and exported to the MATLAB workspace. The objective function used in the optimization is the value of this integral at the end of simulation time. The Simple Driver model is specified by three parameters: gain and time constant for the Transfer Fcn block and delay time for the Transport Delay block. These three parameters are set to be the variable parameters during optimization. The file *Example_5_Simulink_Actuator/obj_find_simple_valve_driver_param.m* implements the objective function and the script file that runs the optimization is *Example_5_Simulink_Actuator/find_simple_valve_driver_param.m*

The optimization was performed with the *fminsearch* function took 35 iterations and 83 objective function assessments to find the optimal set of parameters. Figure 16 shows the characteristics before and after optimization.
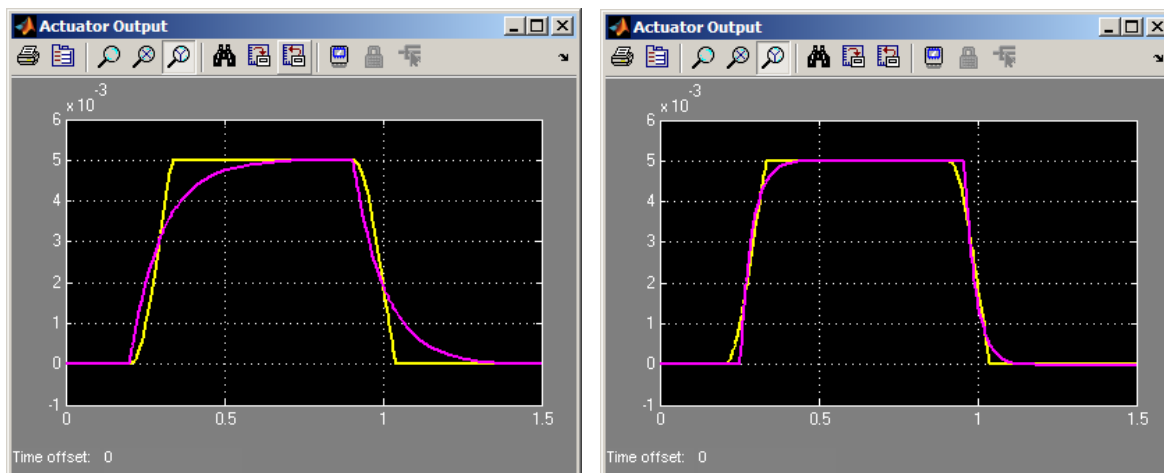

Figure 16. Valve actuator characteristics: a) before optimization b) after optimization.
The yellow line corresponds to the SimHydraulics 2-Position Actuator.

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3.2. Transient Response Characteristics with SimHydraulics Proportional and Servo-Valve Actuator

The dynamic properties of proportional and servo-valves are frequently characterized with transient response characteristics. To account for inherent nonlinearity of valves, data sheets often provide two or even three characteristics at different input signals (for example 10%, 20%, and 100% of the rated signal). To determine accurate parameter values for the Proportional and Servo-Valve Actuator, all specified characteristics must be considered simultaneously.   The SimHydraulics Proportional and Servo-Valve Actuator block must be parameterized to produce transient responses as shown in Figure 17. As can be seen, the responses are quite different. The overshoot of the 20% response is over 25%, while the overshoot of the 100% response is lower than 7%. The response times are also quite different.
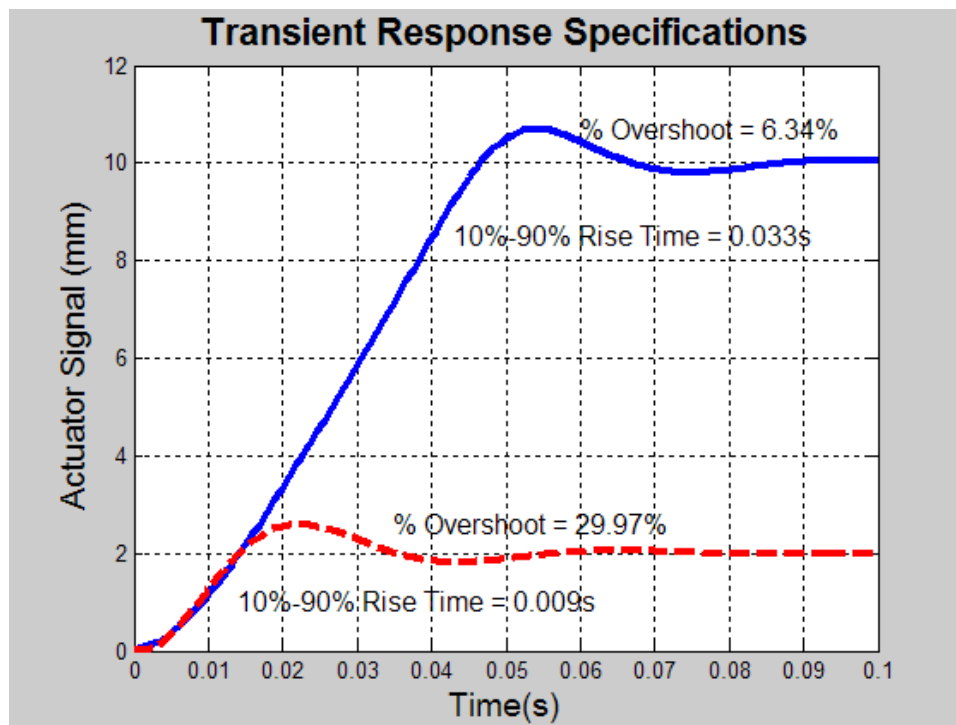

Figure 17. Transient responses of the actuator at different levels of input signal.

One method of solving this kind of problem is shown in Figure 18 and saved in the file *Example_6_Prop_Servo_Trans_Resp/transient_response_match_test_rig.mdl*
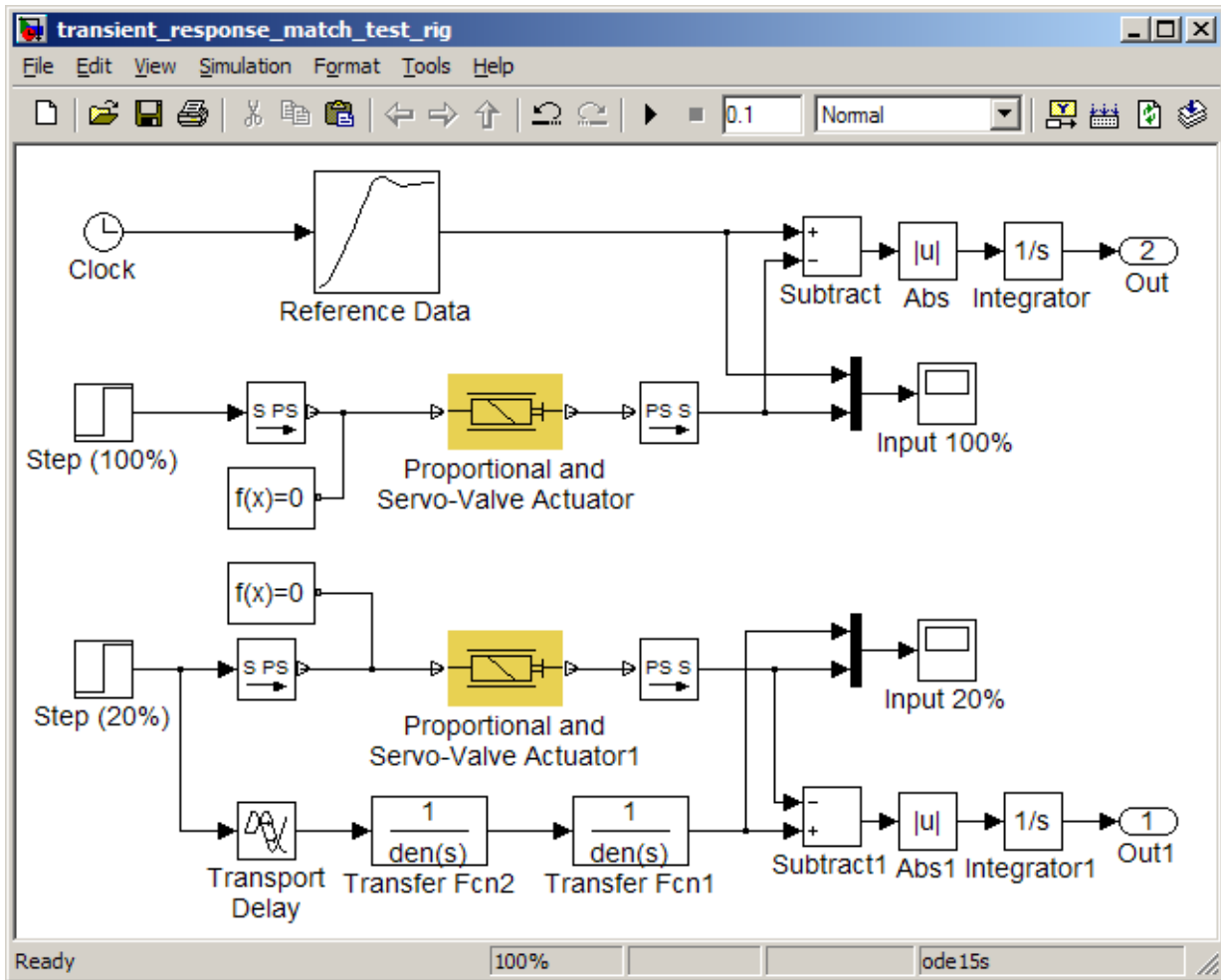
Figure 18. Test rig for actuator transient response optimization.

The model contains two independent tests, one simulating behavior at full signal (10 V in this case), while the other (the lower portion of the model) determines transient response at 2 V, or 20% of the rated signal. The required transient response can be specified multiple ways, including the Simulink Lookup Table block or a simple combination of Simulink blocks. The lookup table is the best option if the response is highly nonlinear. If the shape of the response is close to the characteristic of linear or slightly nonlinear elements and can easily be matched with Simulink blocks, the second method is preferable. Using Simulink blocks when possible is recommended for it will shorten simulation times and help filter out noise due to measurement error. The use of the System Identification Toolbox™ is highly recommended for this operation. In this example, the 100% response is specified with the lookup table block and the 20% response is specified using Simulink blocks.

The difference between the required and the actual transient responses is determined by integrating the absolute value of the difference of those responses. The objective function has the following form

$$\min F(x) = \sum_{1}^{2} \alpha_i \int |z_r(t) - z_a(t)| dt \qquad (7)$$

where

x Variable parameters. They are the parameters of the actuator: gain, time constant, and saturation,

α_i Weight multipliers

z_r Required transient response

z_a Actual (measured) transient response.

The search is performed with the MATLAB optimization function *fminsearch,* which is an unconstrained single-criteria procedure. Matching the transient response is a constrained optimization problem since all three variable parameters must have positive values. To keep variable parameters in the feasible region, a penalty function must be added to the objective function. In this case, the penalty function is introduced as the following

$$\min F(x) = \sum_{1}^{2} \alpha_i \int |z_r(t) - z_a(t)| dt + \sum_{1}^{3} k_i \cdot P_i(x)$$

$$P(x_i) = \begin{cases} (x_i - x_{i\,\min})^2 & if \quad x_i \le x_{i\,\min} \\ 0 & if \quad x_i > x_{i\,\min} \end{cases} \qquad (8)$$

$$i = 1,2,3;$$

where

P(x)   Penalty function.

k_i Weight multipliers

x_{imin} Minimum value of the variable parameter

The file *Example_6_Prop_Servo_Trans_Resp/obj_find_prop_valve_driver_param.m* implements the objective function. The script for running the optimization is saved in the file *Example_6_Prop_Servo_Trans_Resp/find_prop_valve_driver_param.m.* Using *fminsearch*, it took 168 iterations and 403 assessments of the objective function to find parameter values that

minimize the difference between the required transient responses and the simulation results. The transient responses after optimization are shown in Figure 19.
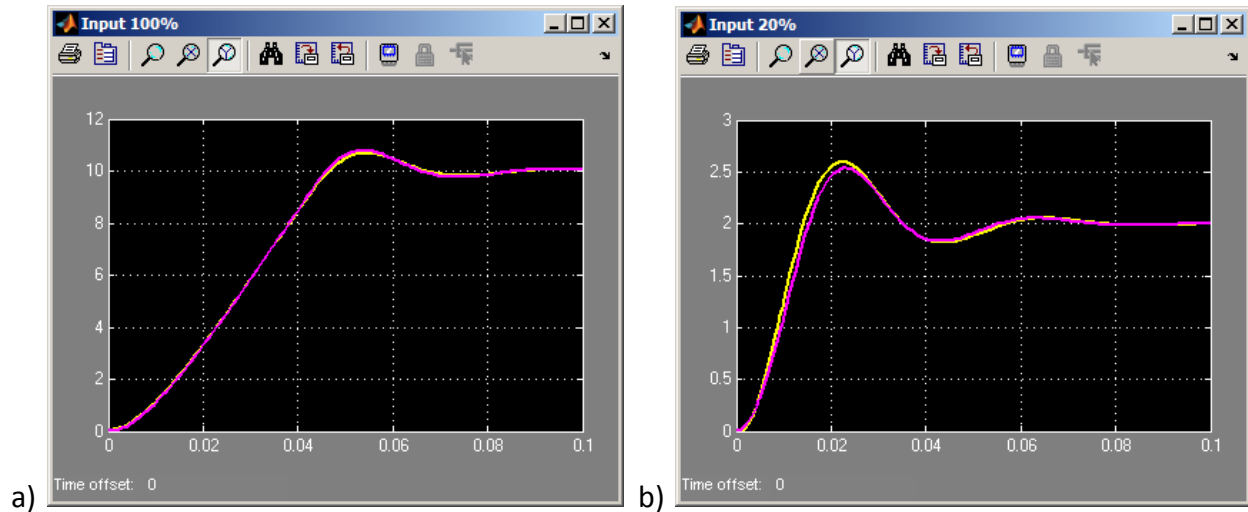

Figure 17. Transient responses of the actuator after optimization: a) 100% input signal; b) 20% input signal. (yellow line represents the required characteristic)

3.3. Frequency Response Characteristics with SimHydraulics Proportional and Servo-Valve Actuator

It is quite common for manufacturers to specify dynamic properties of proportional and servo-valves using frequency response characteristics. Figure 20 shows an example characteristic [1].
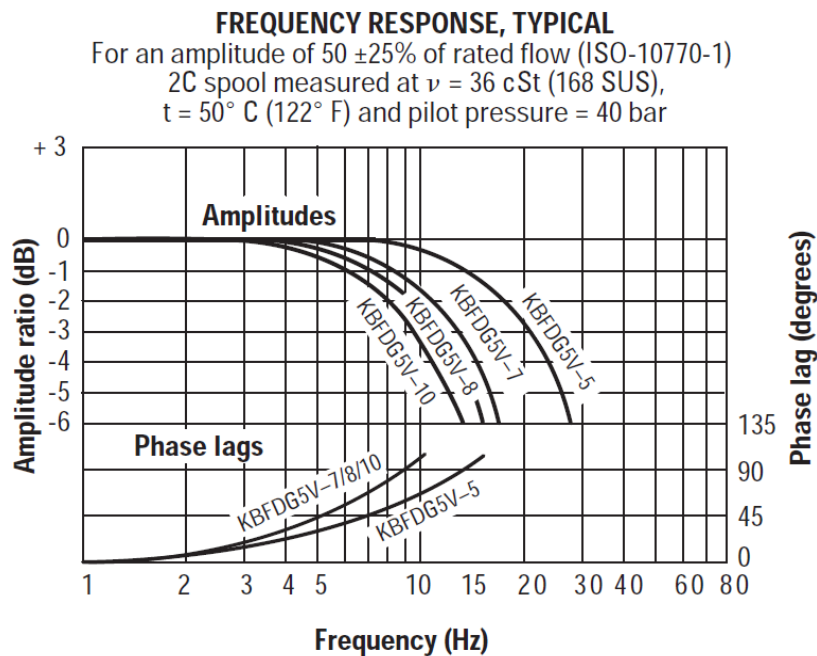

Figure 20. Typical frequency response characteristics of proportional valve.

Due to the inherent nonlinearity of electro-hydraulic systems, the frequency characteristics depend on the value of control signal, supply pressure, fluid properties, and other factors. Therefore, the dynamics are normally specified by a set of characteristics, and each set corresponds to specific values of those parameters. To obtain accurate parameter values for the actuator, all of these parameters must be reproduced in the model and all characteristics must be considered simultaneously.

Theoretically, frequency characteristics are defined for linear systems only. Therefore, the system model must be either linearized to make it suitable for linear system analysis, or the characteristics must be determined by comparing input and output signals at a set of sinusoidal inputs of different frequencies. The output in the second method must be subjected to spectral analysis and only the dominant harmonic should be taken as an output signal. The second method usually requires a substantial amount of computation. As a result it is used only in limited cases and only under conditions that the first method fails or produces unacceptable results.

3.3.1. Matching Frequency Response Characteristics Using Linearization

The linearization of hydraulic systems is not an easy task since substantially nonlinear elements such as saturation and dead zone are present in practically all elements, including the valve actuator. The method described in this section considerably simplifies the linearization and produces acceptable results. The method relies on the formula of the Fourier transform of the pulse transient response, which for linear systems produces exact frequency characteristics

$$H(jw) = F\{\delta(t)\} \tag{9}$$

where

$H(jw)$ Frequency response, $A(w) = mod(H(jw)), \; \varphi(w) = \arg\big(H(jw)\big),$

$\delta(t)$ Pulse transient response

$A(w)$ Amplitude characteristic

$\varphi(w)$ Phase characteristic

If the system under consideration is nearly linear, the same transform can be applied to obtain frequency characteristics. To explain and test this method, it will be used to determine frequency characteristics for a linear system shown in Figure 21 and saved in the file *Example_7_Prop_Servo_Freq_Rresp_Linear/pulse_response_linear_test_rig.mdl*
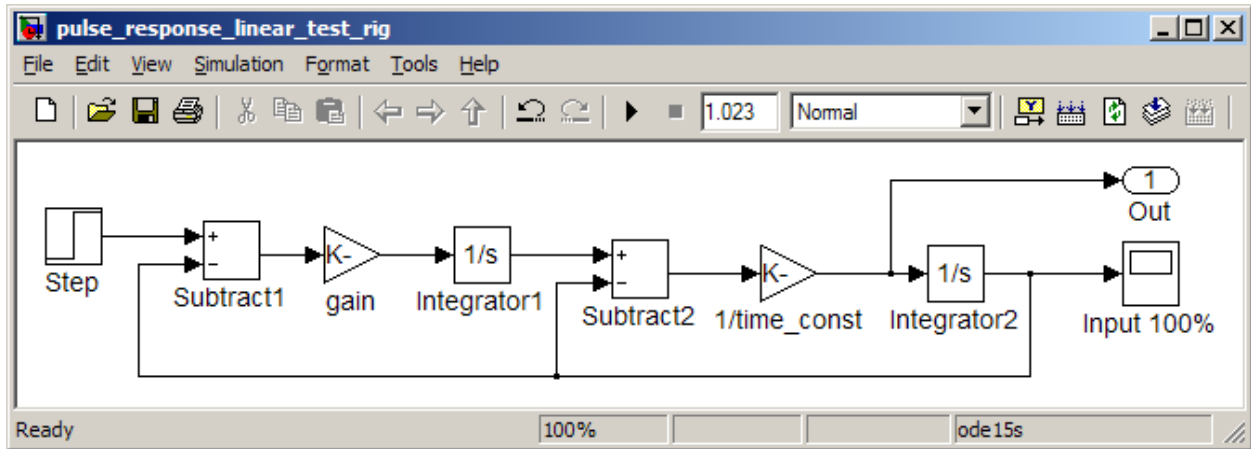
Figure 21. Experimental rig to test the Fourier Transform method.

The transfer function of the closed-loop system corresponds to a second order lag

$$G(\omega) = \frac{1}{\dfrac{1}{\omega_n^{\,2}} s^2 + \dfrac{2\zeta}{\omega_n} s + 1}$$

(10)

where

ω_n	Undamped frequency, $\omega_n = \sqrt{K/\tau}$
ζ	Damping coefficient $\zeta = \dfrac{1}{2}\sqrt{\dfrac{1}{K\cdot\tau}}$
K	System open-loop gain
τ	Time constant

The pulse transient response is determined by applying a step input to the system and measuring the input signal to the second integrator. This is equivalent to applying an ideal pulse at the input and measuring the output, but much easier to implement. To apply a pulse input, the pulse magnitude and pulse duration must be defined. For an ideal pulse, the magnitude must be infinity and the duration must be zero. In numerical simulation, these parameters must be finite, non-zero values, which produces results that do not correspond well to an ideal pulse.

The pulse response is exported to the MATLAB workspace with the Outport block *Out* as shown in Figure 21 and processed with an FFT function to compute the phase frequency characteristic (*Example_7_Prop_Servo_Freq_Rresp_Linear/calculate_frequency_response_characteristic.m*).

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To assess the accuracy, the frequency characteristic was compared to the frequency characteristic of the second order lag computed with the formula

$$\varphi(\omega) = -\arctan \frac{2\zeta \cdot \dfrac{\omega}{\omega_n}}{(1 - \left(\dfrac{\omega}{\omega_n}\right)^2)}$$

(11)

where

ω Frequency

The measured and computed characteristics are shown in Figure 22,a and the difference between characteristics is shown in Figure 22,b. The difference is very small and does not exceed 3 degrees in the relevant range of frequencies.
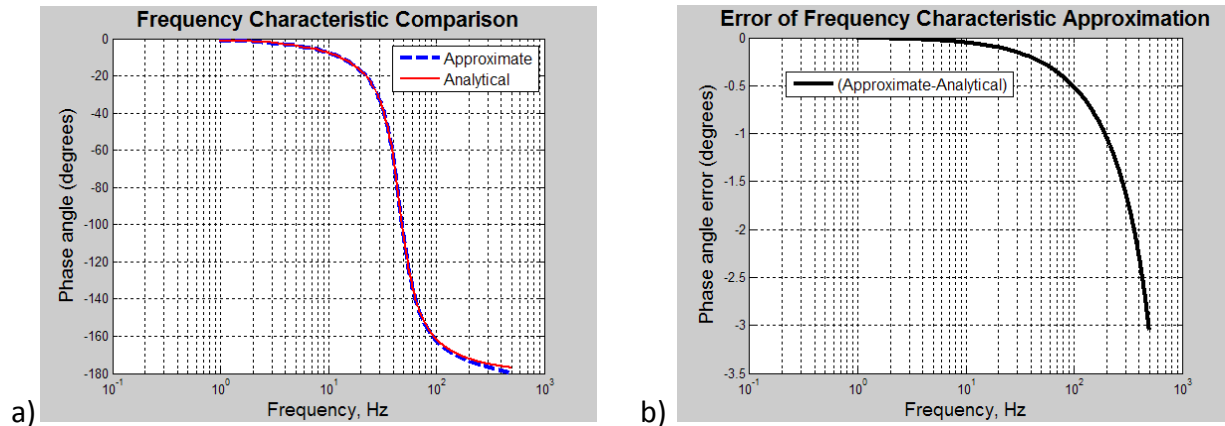

Figure 18. Phase frequency response characteristic:
a) characteristics of the test rig and the second-order lag; b) error of determining the characteristics

Now this method will be used to determine parameter values for the SimHydraulics Proportional and Servo-Valve Actuator block. For the reasons explained in the previous example, the pulse response will be determined by applying a step input. The model of the actuator used for determining these parameters is built using Simulink blocks so that intermediate variables can be accessed. The model is shown in Figure 23, and the structure of the model is described in the SimHydraulics documentation.
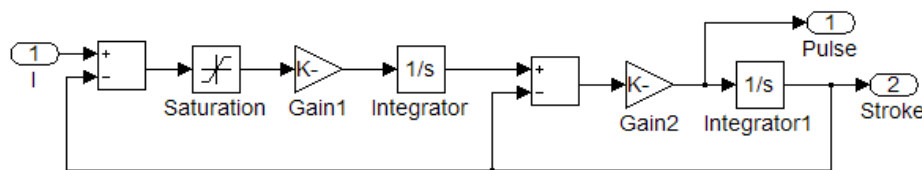

Figure 23. Structural model of the SimHydraulics Proportional and Servo-Valve Actuator

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The Outport block named Pulse is added to the model to export the pulse characteristic to the MATLAB workspace. For simplicity sake, the displacement of the actuator push-pin which is directly connected to the valve spool is taken as the output signal. If the characteristic in the catalog relates output flow rate or some other parameter (pressure, cylinder displacement, etc.) the model must be enhanced to reflect the real environment.

The valve actuator is characterized based on frequency response characteristics at 20% and 100% of the input signal whose maximum value is 10 V. The parameter values are assumed to be acceptable if the frequency at which a phase shift of -90 degrees occurs is close to the values in the manufacturer data sheet. For this example, the frequency at -90 degree phase shift is 10 Hz for the 10 V input signal, and 25 Hz for the 2 V input signal. The variable parameters are the gain, time constant, and the saturation of the actuator model.

 Figure 24 shows the model of the test rig used to determine the parameter values (see *Example_8_Prop_Servo_Freq_Resp_Direct/actuator_freq_testrig_pulse_FFT_method.mdl* file). The same model of the actuator is excited by both a 10 V step input and a 2 V step input. Similar to the circuit in Figure 21, the output signals are measured at the input to the last integrator.
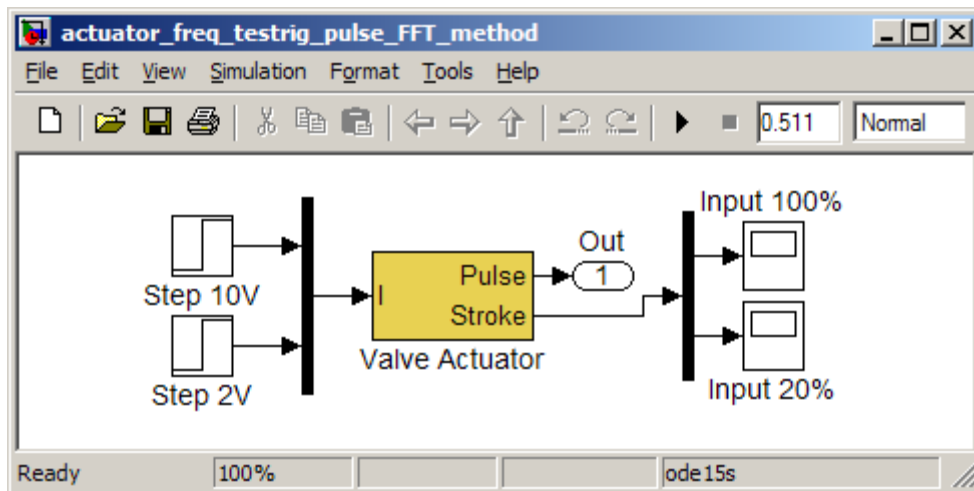

Figure 19. Test rig for the actuator parameterization with the FFT of the pulse response method.

The simulation is set to run for 0.511 seconds to generate 512 samples in the time series. The frequency response is generated with the FFT algorithm and the frequency at which -90 degree phase shift occurs is determined using interpolation. For details, see the script file *Example_8_Prop_Servo_Freq_Resp_Direct/find_actuator_param_pulse_FFT_method.m.*

The objective function for the task is

$$\min F(x) = \sum_{1}^{2} \alpha_i (f_r - f_a)^2 \qquad (12)$$

where

x	Variable parameters. They are the parameters of the actuator: gain, time constant, and saturation
α_i	Weight multipliers
f_r	Required frequency value
f_a	Actual (measured) frequency value
i	Input levels tested (100%, 20% in this example)

The objective function is implemented in the file *Example_8_Prop_Servo_Freq_Resp_Direct/ obj_actuator_param_pulse_FFT_method.m* and the script to run the optimization is *Example_8_Prop_Servo_Freq_Resp_Direct/find_actuator_param_pulse_FFT_method.m*

The search was performed with *fminsearch* function in MATLAB. It took 75 iterations and 178 assessments of the objective function to determine the valve actuator parameter values.

To determine the accuracy of the results, two methods were used. The first is the same method used to find the parameter values (pulse transient response-FFT method). By calculating the FFT transform of the pulse transient response, the following frequencies correspond to the 90 degree phase shift at the 20% and 100% input levels:

Frequency Characteristics with Parameters Tuned Using Pulse Response Method
Frequencies Measured Using Pulse Response Method

Frequencies at -90 deg phase shift and 20% input:
Target: 25 Hz   Found: 24.9999 Hz   Error : 0.00023618%

Frequencies at -90 deg phase shift and 100% input
Target: 10 Hz   Found: 9.9999 Hz   Error: 0.00055504%

This method of verifying the results indicates that the parameters found during optimization produce a nearly perfect match with the required characteristics.
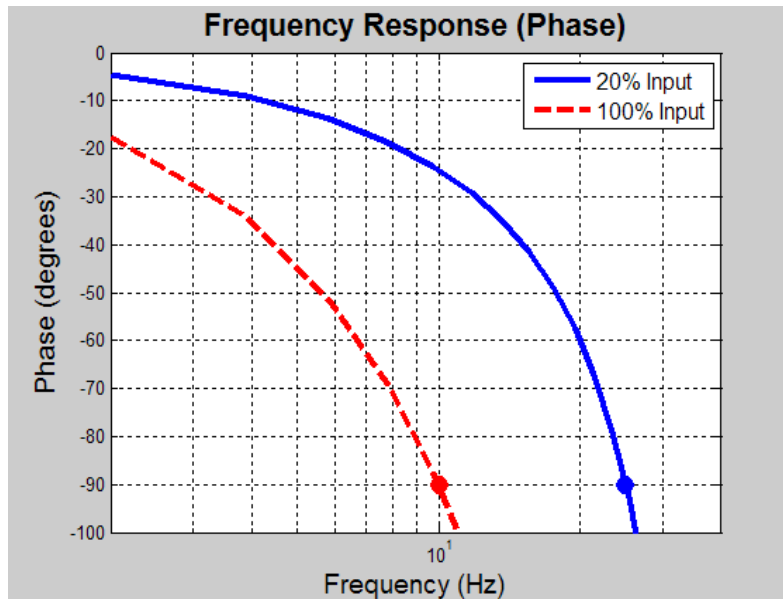
Figure 20. Phase characteristic after optimization at 20% and 100% rated input

The second method performs the check in the time domain. Sinusoidal signals at the specified frequencies and magnitudes are applied to the actuator. After the transients have settled, the phase shift is measured between the input and output signal. The model used for this test is shown in Figure 26.
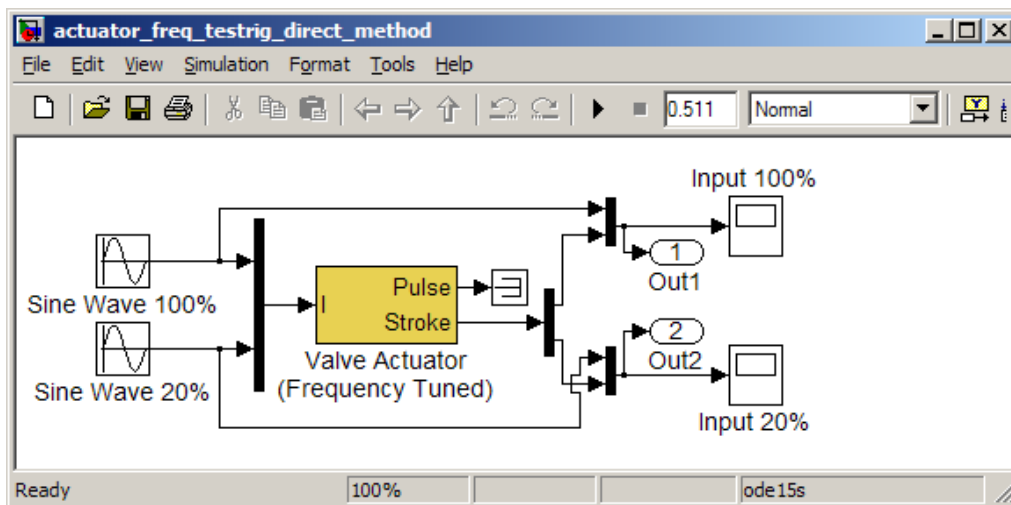

Figure 21. Test rig for phase characteristic measurement in time domain

The phase shift is determined by comparing the input and output sinusoids as shown in Figure 27. The measurement is performed at start time $t_{start} = N \cdot \dfrac{1}{f_{in}}$, where *N* is a whole number of periods, and f_{in} is the frequency of input signal in Hz. For 10 Hz signal the measurement started at 0.4 s and for 25 Hz signal the phase is measured after 6 periods. It is essential to wait a

sufficient number of periods to allow all transients to settle down. Some preliminary experiments with the model should be performed to determine how many periods to wait. The phase angle is computed as $\varphi = \tau/T \cdot 360$, where T is the period, and τ is the delay of the output signal.
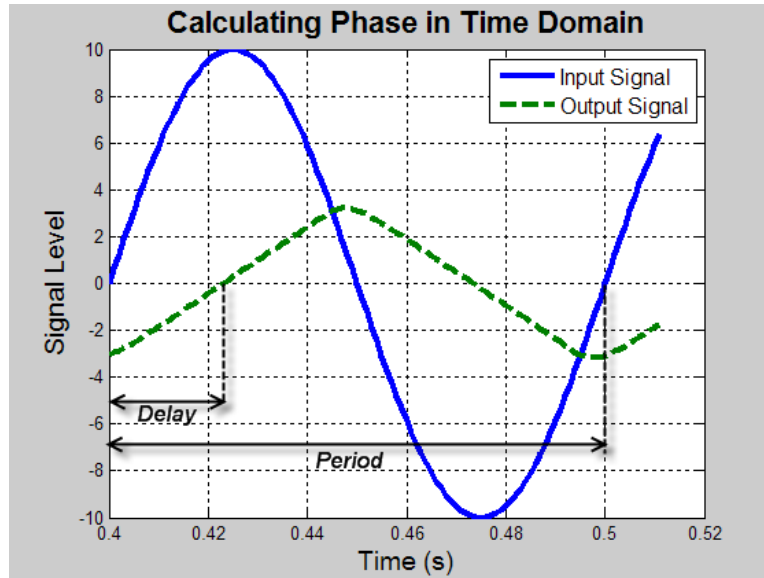

Figure 22. Plot explaining phase shift measurement in time domain

Direct measurement of the phase lag in the time domain indicates that the identified parameter values are not accurate enough.

Frequency Characteristics with Parameters Tuned Using Pulse Response Method
Phase Measured in Time Domain

Phase shift at 25Hz and 20% input:
        Target: -90 deg   Found: -126.3294 deg   Error : -40.366%

Phase shift at 10Hz and 100% input
        Target: -90 deg   Found: -94.7396 deg   Error: -5.2663%

The error is too large for the parameters to be accepted. To improve these results, the pulse transient response method for determining these parameters can be repeated with additional time samples until the results can be accepted. Other methods include performing a spectrum analysis on the model or using direct measurement in the time domain to determine the parameters. The Spectral Analyzer Tool is available in Simulink (enter *sf_spectrum_analizer* in

the command line to invoke the Tool). An example of using this tool for computing frequency response of the valve actuator is saved in the file *Example_8_Prop_Servo_Freq_Resp_Direct/spectrum_analyzer_valve_actuator.mdl.*

The usage of the direct measurement method is described in the next section.

3.3.2.   Matching Frequency Response Characteristics with Direct Measurement

This method of matching frequency characteristics is based on the direct measurement of the input and output sinusoidal signals shown in Figure 27. The model shown in Figure 26 is used to test the system with two sinusoidal inputs. An optimization algorithm is used to tune the same parameters (gain, time constant, and saturation) to minimize the deviation of the phase from -90 degrees at the given frequency. The method for computing phase angle was shown and explained in Figure 27. The objective function is implemented in the file *Example_8_Prop_Servo_Freq_Resp_Direct/obj_actuator_param_direct_method.m.* The script file *Example_8_Prop_Servo_Freq_Resp_Direct/find_actuator_param_direct_method.m* runs the optimization.

 The results of the search with the direct measurement method are shown below:

Frequency Characteristics with Parameters Tuned In Time Domain
Phases Measured In Time Domain

Phase shift at 25Hz and 20% input:
     Target: -90 deg   Found: -92.6008 deg   Error :   -2.8898%

 Phase shift at 10Hz and 100% input
     Target: -90 deg   Found: -83.2452 deg   Error: 7.5053%

The method produced results that are an acceptable match to the required characteristics.

4. Conclusion

The problem of parameterization of SimHydraulics directional valve models is considered in the paper. All methods presented in the paper are based on the application of optimization procedures with either the MATLAB general function *fminsearch* or a function from the Optimization Toolbox™.

Objective functions formulated for parameterization of both the power and control stages of directional valves were considered.

Two methods of determining the power stage parameter values were presented: (1) by tuning the parameter values to match required characteristics (2) by calculating the valve parameter values using experimental data.

In SimHydraulics, valve dynamics are accounted for in the model of the control stage. Both methods of dynamics characterization (transient response, frequency characteristics) are considered in this paper. The required characteristic in the time domain can be specified as either a lookup table or a combination of Simulink blocks. The frequency response can be determined using the approximate method based on the Fourier transform of the valve pulse characteristic or by applying a direct measurement method.

5. References

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